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HEAT TRANSMISSION AND TRANSFER AND A STUDY OF THE HEAT  
TRANSFERENCE FROM A CAST IRON PARTITION TO VARIOUS SOLUTIONS

by

WALTER BIRSACH SCHULTE

A Thesis Submitted for the Degree of  
CHEMICAL ENGINEER

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P A R T    I.



# HEAT TRANSMISSION AND TRANSFER AND A STUDY OF THE HEAT TRANSFERENCE FROM A CAST IRON PARTITION TO VARIOUS SOLUTIONS

## Introduction.

The question of heat transfer from one medium to another, through a partition is one of great importance, and many measurements have been made of the quantities of heat transferred under different conditions. As examples of common commercial apparatus in which the principle of heat transfer through a partition is involved, may be cited; steam boilers and condensers, evaporators and dryers, gas retorts and condensers, muffle and electric furnaces.

In most of the experiments made to determine the total heat transferred, between two media, the measurements were made on one type of apparatus under different conditions<sup>and</sup>, the results were generally satisfactory. The results obtained from tests on one type of apparatus, however, would not always agree with the results obtained on another though similar type, the reason being that some of the governing factors had not been exactly reproduced in both cases. Some of the factors influencing the transfer of heat are:-- (a) radiation, (b) the position, conductivity, thickness and surface finish of the partition, (c) the velocity, temperature, specific heat and nature of the gases or liquids, etc.

The object of this investigation is to measure





the heat transfer resistance between a cast iron partition and various solutions, and was limited to a study of the transfer resistance between the partition and the liquid, only, instead of the total resistance between the two liquids separated by the partition. The first part is a compilation of the most important experimental work in heat transference.

Transmission, in the following, means the passage of heat in a single homogeneous medium and Transfer the passage of heat from one medium to another.



Section 1.

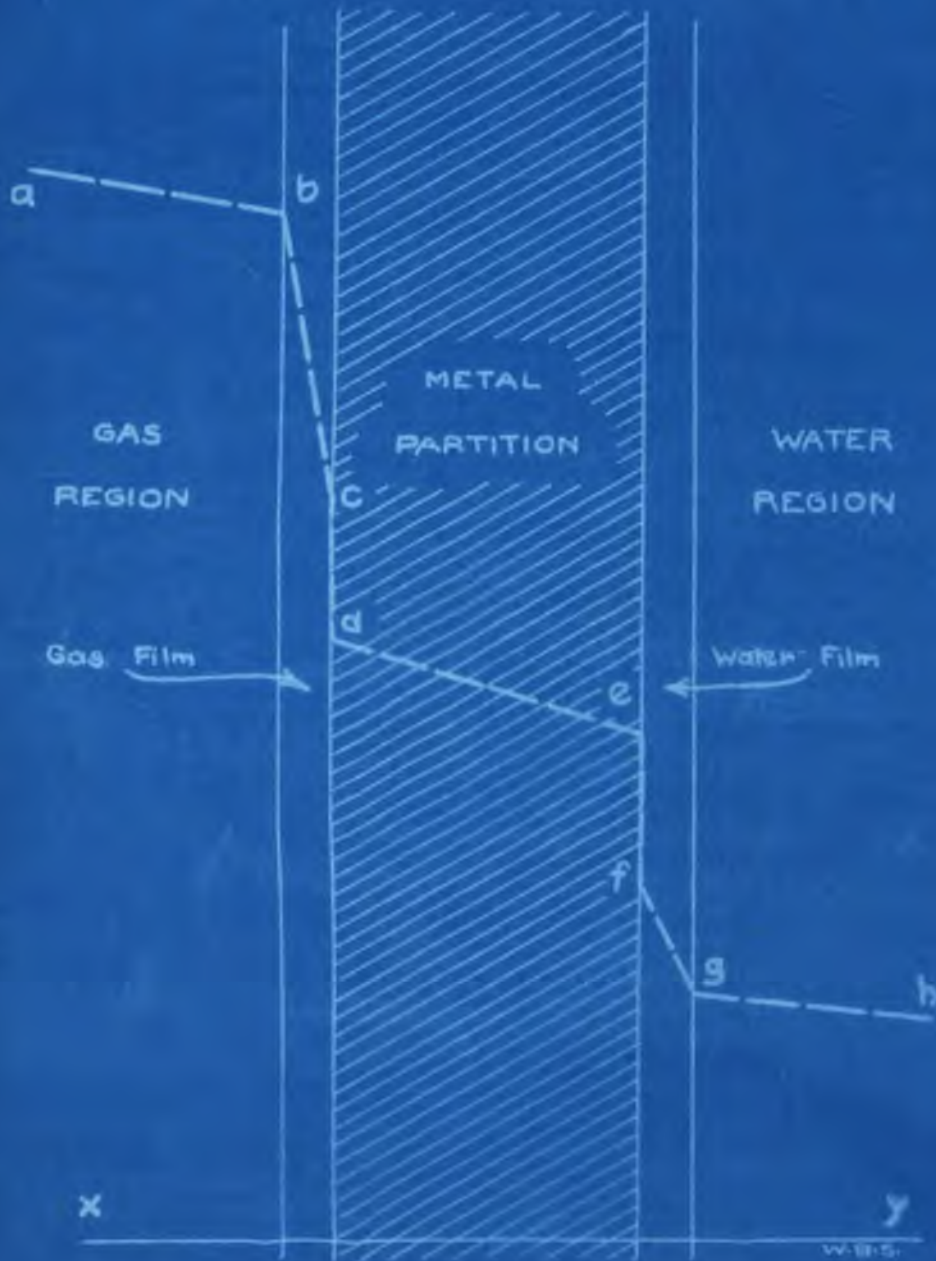
The Surface Film.

The mechanism of heat transmission in a homogeneous solid body is comparatively simple as the amount of heat passing depends solely upon (a) the temperature difference, (b) conductivity of the material, (c) its cross-section and thickness and (d) on the time. When heat leaves one body and passes into another the factors influencing the transfer become more numerous and less comprehensive. This is especially the case where the transfer is between a liquid or gas and a metal.

It is well known that water can be evaporated in a paper cup over a flame or that a postage stamp can be pasted on the hot side of a boiler tube and even though it is subjected to the hot gases it will not char. It is assumed that there is a thin film of inert gas on the surface of the flue and that its resistance is high enough to consume considerable temperature head on the passage of heat. The transfer through this film and the partition is illustrated on Plate I. The partition is shown and the temperature is represented by the vertical distance of the dotted line from the base (x) (y). Starting from the center of the gas region at (a), there is but a slight temperature drop to (b), at the surface of the gas film; from



# PLATE I





(b) to (c) there is a considerable temperature drop. Professor Dalby<sup>(1)</sup> assumes that there is another temperature drop, ((c) (d)) at the surface of contact between the gas and the partition. From (d) to (e) the drop is due to the resistance of the metal itself, (e) to (f) is the exit drop between the plate and water, and (f) to (g) the drop through the water film. (g) to (h) shows very little drop and it has been found that there is often no difference between<sup>(2)</sup> the water at the surface of the film and at the center (b).

Assuming the presence of such a film, the extremely high resistance at the surface of the plate can be accounted for by the fact that this film clings tenaciously to the surface and the transfer of heat through it by convection currents is small. The only means, then, by which the heat can reach the plate is by conduction or radiation. Radiation is an important factor in the transfer in boilers, but in apparatus, such as evaporators or condensers, where comparatively low temperatures are used, its effect, as far as the heat exchange is concerned, is almost nil.

(1) Heat Transmission P. I. M. E. 1909 p. 921.

(2) Heat Transfer Through Partitions. Austin.  
Zeit. d. Ver. d. Ing. 1902 46 1860.





Conduction then is the only agency by which the heat can traverse the film and as the thermal conductivities of gases and liquids are hundreds of times lower than that of metals, a thin film would account for the tremendous temperature drop at the contact surface between a gas or liquid and a metal.

(1)  
Mr. Fletcher experimented with layers of paper on the contact surface between hot gases and a metal and noticed that when the paper thickness was over one-fortieth of an inch the surface would char. It might be assumed then, that the gas film is of this thickness.

From measurements made by the German Reichanstalt on the transfer resistance between metals and water the thickness of the water film was computed to be 0.5m.m. (2)  
(3)  
and 0.1 m.m. The experiments and results of this work is discussed in full in Part II, pages 55 to 66.

(1) Dalby. Heat Transmission. Proc. Inst. M. E. 1909 921

(2) Holburn & Dittenberger. Heat Transfer through Partitions. Zeit. d. Ver. d. Ing. 1900 44 1724

(3) Austin. Heat Transfer through Partitions. Zeit. d. Ver. Ing. 1902 46 1860



Section 2.

Contact Resistance.

Although not of any importance in the transfer of heat through single metal walls, contact resistance is of some importance where heat passes from one solid body to another. Heat travels along a solid copper bar faster than it does along a bar made up of short sections screwed together, the reason being that there is a resistance at each joint. Mr. Snyder<sup>(1)</sup> recognizes that the resistance between layers of brick in furnace walls is of as much influence as a resistance to the flow of heat as the bricks themselves. Mr. Carl Hering<sup>(2)</sup> gives an instance of contact resistance. A graphite electrode was being used in an electric furnace and it happened that the joint where one section of the electrode was screwed into the other was just above the furnace top. It was noticed that below the joint the electrode was red hot while above the joint it was black, thus showing a large heat gradient across the joint.

(1) Hering. Flow of Heat through Furnace Walls.  
Trans. Amer. Elec. Chem. Soc. 1910 23 235

(2) Discussion. Trans. Amer. Elec. Chem. Soc.  
1910 23 245



Fusible plugs, therefore, cannot be taken as indicators of the temperature of the surrounding metal.

Proiessor Dalby <sup>(1)</sup> believes that there are two temperature drops, c-d and e-f, Plate I, due to contact resistance between the partition and the films.

(1) Proc. Inst. M. E. 1909 3-4 921



Section 3.

Formulae for Transfer.

The heat which one medium gives up through a partition to another medium has to overcome three resistances, viz:-

- (1) The entry from the first medium through the surface film into the partition.
- (2) The resistance of the partition itself.
- (3) The exit from the partition through the surface film into the second medium.

(1)  
Peclet expresses the total resistance as the sum of three single resistances, taking for each a coefficient which gives the total number of heat units passing through unit surface in unit time under unit temperature difference. The entry coefficient is represented as ( $a_1$ ) the exit coefficient by ( $a_s$ ), the conductivity of the partition by ( $e$ ), the thickness by ( $d$ ) and the heat passing by ( $Q$ ) The heat passing through each resistance is the same and can be expressed by the following:-

$$\begin{aligned}
 Q &= a_1 \cdot Z \cdot F \cdot (t_1 - d_1) \\
 Q &= \frac{e}{d} \cdot Z \cdot F \cdot (d_1 - d_s) \\
 Q &= a_s \cdot Z \cdot F \cdot (d_s - t_s)
 \end{aligned}
 \tag{1}$$

(1) "Traite de la Chaleur".





in which (Z) is time, (F) the cross-section of the partition,  $(t_1)$  and  $(t_2)$  the temperatures of the hot and cold media respectively, and  $(d_1)$  and  $(d_2)$  the corresponding temperatures of the surfaces of the partition. Combining we get

$$Q = \frac{1}{\frac{1}{a_1} + \frac{d}{e} + \frac{1}{a_2}} \cdot Z \cdot F \cdot (t_1 - t_2) \quad (2)$$

Peclet also suggests the substitution of

$$\frac{1}{K} = \frac{1}{a_1} + \frac{d}{e} + \frac{1}{a_2}$$

so  $K = \frac{1}{\frac{1}{a_1} + \frac{d}{e} + \frac{1}{a_2}} \quad (3)$

which is called the coefficient of total transfer. It is seen that the ratio  $\frac{d}{e}$  can be computed leaving  $\frac{1}{a_1} + \frac{1}{a_2}$  the two transfer coefficients which, until recently, have not been measurable separately. Hausbrand puts--

$$\frac{1}{K_0} = \frac{1}{a_1} + \frac{1}{a_2} \quad (4)$$

thus (3) becomes

$$K = \frac{K_0}{1 + K_0 \frac{d}{e}}$$

(1) "Evaporating and Condensing Apparatus."



(1)

Mollier, in an excellent and complete article, gives the equation for finding the average value of (F) when the two surfaces of the partition are not of the same shape or size. For tubes of circular cross-section the diameter corresponding to the average face is given as,

$$D = \frac{\frac{a_1}{a_2} + \frac{a_2}{a_1} + d}{\frac{a_1}{a_2 D_1} + \frac{a_2}{a_1 D_2} + \frac{1}{2} \log_e \frac{D_2}{D_1}} \quad (5)$$

where ( $D_1$ ) and ( $D_2$ ) represent the diameters of the warm and cold surfaces, ( $D_i$ ) and ( $D_o$ ) represent the inner and outer diameters of the tube. When  $\frac{D_o}{D_i}$  is nearly unity, as is generally the case, then for  $\frac{a_1}{a_2} = \frac{a_2}{a_1}$ ,  $D = \frac{D_1 + D_2}{2}$ ; if one coefficient is large as compared with the other so that  $\frac{a_1}{a_2}$  or  $\frac{a_2}{a_1}$  approaches zero, then D is almost  $D_1$ . It then follows that when the coefficients differ considerably, the tube should be arranged so that the heat flows from the smaller coefficient either in or out.

If the two media change their temperatures due to an exchange of heat the following formula is necessary. Let ( $G_1$ ) and ( $G_2$ ) be the masses of the media, ( $c_1$ ) and ( $c_2$ ) their specific heats which are constant, ( $a_1$ ) ( $a_2$ ) (d) and (K) also remain constant. ( $t'$ ) and ( $t''$ ) are the original

(1) Heat Transference and Transference Experiments  
Zeit. d. Ver. d. Ing. 1897 41 153 & 197



and final temperatures of the masses.

$$Q = K.F.Z \frac{(t'_1 - t'_2) - (t''_1 - t''_2)}{\log_e \frac{t'_1 - t'_2}{t''_1 - t''_2}} \quad (6)$$

If both media flow along the partition at the same time the temperature of one will drop from  $(t'_1)$  to  $(t''_1)$ ; the temperature of the other will rise from  $(t'_2)$  to  $(t''_2)$ .  $t'_1 \geq t'_2$  depending on whether the liquids flow counter or parallel. The expression takes the same form as (6) or by substituting  $c_1 G_1 (t'_1 - t''_1)$  or  $\pm c_2 G_2 (t''_2 - t'_2)$  for (Q) it can be written

$$K.Z.F = \frac{\log_e \left( \frac{t'_1 - t'_2}{t''_1 - t''_2} \right)}{\frac{1}{c_1 G_1} \pm \frac{1}{c_2 G_2}} \quad (7)$$

where the negative sign is for the condition of counter flow.

When  $\frac{t'_1 - t'_2}{t''_1 - t''_2}$  approaches unity the above

equation can be simplified to

$$Q = K. Z. F. \left( \frac{t'_1 + t''_1}{2} - \frac{t'_2 + t''_2}{2} \right) \quad (8)$$

The error of using (8) becomes greater as



the ratio deviates from unity. Below is a table from Mollier showing the error resulting when the ratio is not unity.

$\frac{t_1 - t'_2}{t''_1 - t''_2}$	1.5	2	3	4	5	10	100
error	1.014	1.038	1.019	1.154	1.210	1.410	2.35

When heat is exchanged between two media, the mean temperature difference between them, as derived by Hausbrand<sup>(1)</sup> is

$$t_m = \frac{t_b - t_e}{\log_e \frac{t_b}{t_e}} \quad (9)$$

where  $(t_b)$  and  $(t_e)$  are the temperature differences between the media at the beginning and at the ends of flow. This equation holds for all cases of parallel or counter flow.

(1) "Evaporating and Condensing Apparatus."





Section 4.

Influence of Radiation.

A partition can receive heat from a medium; a liquid for instance; in three ways, viz:--

- (1) By conduction from the liquid to the partition surface.
- (2) By convection, e. g. the continuous movement of the hot particles of the medium to the plate and the continuous removal of the cooled particles.
- (3) By radiation.

The experimental investigations on the effect of the first two factors will be dwelt on in the following sections. In regard to radiation, Mollier<sup>(1)</sup> says that when the surface of the partition is near other bodies at a different temperature, a heat exchange will take place between the two. This heat exchange due to radiation must be added to the exchange taking place from other causes. The magnitude of the exchange by radiation is found to depend on the following:-

- (1) Zeit. d. Ver. d. Ing. 1897 41 153 & 197.



- (1) On the condition of the surfaces of the bodies, e. g., on the ease with which they give up or take up the heat rays. (Emissive of absorptive power).
- (2) On the size and form of both surfaces which determine the number of heat rays emitted or absorbed.
- (3) On the temperatures of both bodies which determine the intensity of the rays.
- (4) On the power of the intervening medium to transmit the rays.

Absorptive and emissive powers are the same and will therefore be called radiant power. Highly polished surfaces, such as metallic surfaces, have the lowest power to radiate heat and their coefficient is 0. Dull black has the highest power of radiation and the coefficient in this case is 1.

The rays which a single element of a surface sends out can be branded by a hemisphere.  $\phi$  represents the ratio of the rays, from an element, which strike another body to the total number of rays emitted. This ratio is not the same for all the elements of the surface but an average,  $\phi_I$ , can be determined so that its product with the total surface will represent the rays sent out which strike the



other body. If  $F_I$  is the surface of the first body,  $F_{II}$  the surface of the second, and  $\phi_I$  and  $\phi_{II}$  the ratios mentioned, then  $F_I \phi_I = F_{II} \phi_{II}$ . If all the rays sent out by one body hit the other, then  $\phi = 1$ .

More heat is radiated from a hot body than from a cold one. The heat transferred depends on the temperature difference and increases with an increase of temperature of the hot body or a decrease of the temperature of the cold one.

In view of what has been said, then, the heat (R) passing in the time (Z) from a warm body (I) to a cold body (II) can be expressed as--

$$R = Z \cdot p_I \cdot \phi_I \cdot F_I \cdot f(t_I, t_{II}) \quad (10)$$

where the value of the radiation powers are represented by  $(p_I)$  or  $(p_{II})$ .

If the hot surface of a partition takes up the heat  $(R_1)$  from some other body by radiation and gives up  $(R_2)$  from the cold surface, then the following relations will hold where  $(Q)$  is the flux through the partition.

$$\begin{aligned} Q &= a_1 \cdot F \cdot Z \cdot (t_1 - d_1) + R_1 \\ Q &= \frac{e}{d} \cdot F \cdot Z \cdot (d_1 - d_2) \\ Q &= a_2 \cdot F \cdot Z \cdot (d_2 - t_2) + R_2 \end{aligned} \quad (11)$$



Solving and substituting

$$K = \frac{1}{\frac{1}{a_1} + \frac{d}{e} + \frac{1}{a_2}}$$

we get

$$Q = K \cdot F \cdot Z (t_1 - t_2) + K \left( \frac{R_1}{a_1} + \frac{R_2}{a_2} \right) \quad (12)$$

Numerous experiments have been made to determine the value of the function  $(t_1 - t_2)$  and some of the determined values have been found to differ considerably from each other.

(1)

Dulong and Petit made the first radiation experiments and with  $\phi = 1$  and  $p = 1$  they express

$$f(t_1 - t_2) = 1.0077 t_1 - 1.0077 t_2 \quad (2)$$

Rosetti gets

$$f(t_1 - t_2) = (a T_1^2 - b) (T_1 - T_2)$$

in which  $T_1$  and  $T_2$  are the absolute temperatures of the bodies and  $a = 0.0000033513$  and  $b = 0.0637$

(3)

Mollier, on the basis of Peclet's work gives

(1) Ann. d. Chem. et Phys. 7 225

(2) Ann. d. Chem. et Phys. 17 177

(3) Zeit. d. Ver. d. Ing. 1897 41 153 & 197





the following simpler formula for radiation in practical work,--

$$R = 0.55. Z. F_I \phi_I. P_I \left\{ \left( \frac{T_I}{100} \right)^2 - 1.9 \right\} (T_I - T_{II}) \quad (13)$$

(1)

Stefan derives the following from the work of several investigators ;

$$r(t_I t_{II}) = (T_I^4 - T_{II}^4)$$

for practical work Mollier writes this as

$$R = 4.33. Z. F_I \phi_I. P_I \left\{ \left( \frac{T_I}{100} \right)^4 - \left( \frac{T_{II}}{100} \right)^4 \right\} \quad (14)$$

and in regard to the various equations says that at low temperatures,-- say up to 300°C.,-- they all give about the same results. In Dulong and Petit's the radiation increases the most rapidly with  $T_I$ ; in Rosetti's it increases slowest. For high temperatures, such as are encountered in boilers, he recommends the use of Stefan's formula, as it has been found by experience to be most accurate.

(1) Wiener Berichte, 79.



Section 5.

Influence of Partition Thickness.

"In the transfer of heat through a thin partition of iron or copper, from a hot substance on one side to water or gas on the other, the transmission of heat through the partition is sensibly the same as if the thermal conductivity of the metal were infinite."

Lord Kelvin on "Heat". Eucly Brita.

The nature of the partition, with the exception of changes due to the surface conditions, only affects the total transfer through a change of conductivity. The coefficient K from the nature of the equation (3) decreases more with increasing thickness for a poorly conducting metal than for one which conducts well.

(1)  
Sulzer experimented with tubes of various materials and diameters. Steam was allowed to pass through the tubes which rested horizontally in a vessel of water and the loss by evaporation of which was measured by weighing. His results are subject to two errors; no correction was applied to account for radiation or no means taken to pre-

(1) See Mollier, Zeit. d. Ver. d. Ing., 1897, 41, 153 & 197.



vent it; and the air content of the steam was unknown. (See Section 7 for the effect of air in steam). The results, however, tend to show that the partition thickness has but little effect on the total transfer.

(1)

Morrison experimented with cast engine cylinder liners placed in a vertical position with steam on the outside and water on the inside. The transfer was determined for different thicknesses and is expressed in relative values in the following table:--

<u>Thickness inches</u>	<u>Heat Transfer relative values</u>
0.90	100
0.42	149
0.19	202

This shows a considerable change of transfer with thickness.

(2)

Blechynden experimented with plates of various thicknesses and of different materials. His apparatus consisted of a heat resistant vertical cylinder which was covered by a sheet metal vessel. The plate under investigation formed the bottom of the vessel. A bank of fire burners, burning gas, supplied the heat under the plate. The flame

(1) Transmission of Heat through Cast Iron Cylinder Walls. Proc. Inst. M. E. 1892 482

(2) Transmission of Heat Through Metallic Plates. Proc. Inst. Naval Arch. 1894, and Engineer, 1893 II 98



temperature measurements were made with a Siemens pyrometer. Blechynden finds that there is an increase of transfer with a decrease of wall thickness; for example, the transfer was increased 50 per cent by decreasing the wall thickness from 30.2 m.m. to 3.2 m.m. Mollier says that this increase cannot be accounted for even using the smallest coefficient of conductivity for iron and he believes that the variance is due to experimental errors as the Reichanstalt <sup>(1)</sup> with similar apparatus could not check Blechynden's results.

<sup>(2)</sup> Blechynden also made investigations to compare the transfer through iron and copper plates. He concludes that under the same surface conditions and wall thickness copper and iron transfer heat about equally. He noticed, however, that copper kept a clean surface longer than iron under the influence of the gases. The result of this was that with new plates at the beginning of a test the iron would transfer more heat than the copper. This is accounted for by the fact that the clean surfaces have a poorer radiating power.

The experiments of the Reichanstalt were made

(1) Reichanstalt. Bericht 1895.

(2) Transmission through plates. Engineer 1896.  
I. 509.





with apparatus like Blechynden's but thermocouples were used instead of a Siemens pyrometer for measuring the temperatures. The results show but a slight dependence of the transfer on the wall thickness. The results also agree with Blechynden's on the transfer through copper and iron plates.

(1)  
Hirsch experimented with boiler plates of various thicknesses and surface conditions. He increased the partition thicknesses, in some cases, by soldering on another plate, and noted a decided decrease of transfer, due no doubt to the resistance of the contact faces between the two plates. Hirsch used alloys with known melting points plugged into holes in the plates to indicate the temperatures. It is known that fusible plugs do not give the exact temperatures of the surrounding metal so his work may be open to some criticism.

(2)  
Holburn and Wien in an article on conductivity give the following as coefficients for various metals in c.g.s. units and gram calories:-

- (1) Investigation on the rate of evaporation from the surface most exposed to the fire, also study on transmission through clean plates and plates covered with oil and scale.  
Proc. Inst. C. E. 108 464

- (2) Conductivity Measurements. Zeit. d. Ver. d. Ing. 1896 40 46



TABLE

<b>Cu</b>	<b>0.910</b>	<b>Zn</b>	<b>0.292</b>
<b>Fe</b>	<b>0.156</b>	<b>Sb</b>	<b>0.150</b>
<b>Steel</b>	<b>0.062-0.111</b>	<b>Pb</b>	<b>0.079</b>



Section 6.

Influence of Surface Finish.

The condition of the surface of a partition affects the transference in two ways:- viz. (1) by a change of radiation power; (2) by affecting the character of the film and changing its conductivity. A darkening or roughening of a surface, in general, will increase its radiation coefficient but no relation has been found in which the film resistance and surface finish could be compared with each other.

(1)

Hausbrand says:- "The nature of the surface of the material of the partition seems to be almost without action on the movement of heat".

(2)

Austin made measurements of the film resistance from wrought iron to water and from water to iron. The experimental work and results is described in Part II. He found that there is no difference of heat transfer between that transferred by a clean or dirty plate. It was also noticed that water with rust in suspension gives no different values than does clean water.

(1) "Evaporating and Condensing Apparatus".

(2) Zeit. d. Ver. d. Ing. 1902 46 1860.



Experiments have been made comparing the transfer through tubes with a plane surface to the transfer through the same tubes after they had been grooved or ribs placed on them. Mollier says that it is difficult to draw correct comparisons because of the change of surface area and the difficulty of selecting the proper diameters to substitute in the formulae. Sulzer<sup>(1)</sup> found the increase due to ribs to be ten per cent.

Wilkinson<sup>(2)</sup> compared the evaporation of two similar sheet metal pans, one of which had 14 iron angles sweated on the bottom plate, half inside and half outside. He got 4 per cent better evaporation from the pan with the angles and noticed that the ebullition took place on the plane parts of the surface and not on the angles. The reason for the slight increase is, no doubt, due to an increase of the velocity of the water over the surface caused by the formation of local eddies near the angles. Velocity is an important factor in the transfer.

Jordan<sup>(3)</sup> devised an apparatus for the measurement of heat flow from metal surfaces to liquids. He meas-

(1) See Mollier, page 10.

(2) Heat Transmission Proc. Inst. M. E. 1909 981

(3) Rate of Heat Transmission between Fluids and Metal Surfaces. Proc. Inst. M. E. 1909 p. 1317.





ured the metal surface temperature by a thermocouple which was shielded from the liquid and the junction firmly pressed against the surface. Tubes were used as the metal partitions and the measurements were made with air on the inside and water on the outside. A fine screw thread was cut on the outside of the tube with the object of breaking the flow of water and thus increasing the transference. Contrary to expectations this was not successful and no noticeable increase resulted. It was thought that the bottom of the threads filled with stagnant water which decreased any advantage derived from the shape of the threads.

(1) (2)  
Carpenter and Royse compared the heat flow through plates before and after etching them with nitric acid. The acid eats the surface of the metal leaving a spongy structure of carbon and insoluble impurities and it is to be expected that such a surface would affect the transfer. Carpenter found the greatest decrease of transfer coefficient was 31 per cent and was for a plate which had been pickled for fourteen days. In Royse's experiments the average decrease for the pickled plates was 12.5 per cent.

- (1) Heat Transmission Through Plates treated with acids. Journal Amer. Soc. M. E. 1891 12 174.
- (2) Ibid. Jour. Amer. Soc. M. E. 1891 12 1014.



His apparatus was constructed to have the transfer take place between steam and water and it was found that when the plates were finished with varnish on both sides the decrease was 60 per cent. Carpenter mentions experiments of Chamberlin who found the transfer the same whether the plates were clean, painted with oil or etched with various acids, but a plate etched and then oiled had its coefficient reduced to 67.5 per cent of the coefficient of the untouched plate.

Sulzer found in his experiments that a coat of lacquer decreased the transfer in a tube six per cent.

(1)

Blechynden noticed that dirty plates transferred more heat than clean ones. This increase, as has been said, is due to a change of radiating powers.

It is seen that the results of the different investigators do not lead to the same conclusions but it may be said that an increase of surface does not necessarily mean an increased transference. If the increased surface is of such form as to facilitate the formation of eddies and convection currents the probabilities are that the transfer will be increased. This is shown by a comparison of the experiments made with ribbed tubes and those made with the

(1) Blechynden. See Section 5.



pickled plates. The sponge-like surface of the pickled plates would entrap some of the medium in its interstices where it would become stagnant and offer an increased resistance to the heat flow from the solid metal to the medium. In increasing the surface of a partition then, care should be taken so that the movement of the medium over the new surface is unhindered.



Section 7.                      Influence of the Character  
of the Media and the Position of the Partition.

The amount of heat transferred depends greatly upon the nature of the heating medium; whether it is a gas or a vapor; as it has been found that there is a marked difference in the rates at which they give up heat to a partition. Orrok<sup>(1)</sup> found that with steam as the heating medium the transfer is independent of the velocity. Hausbrand mentions experiments<sup>(2)</sup> in which the transfer from flue gases was proportional to the square root of the velocity. The reason for the difference is that steam being a condensable gas much of its heat-giving power is due to its latent heat of condensation; flue gases on the other hand, are non-condensable and the transfer to the partition depends on the rate at which the cooled particles of the gas at the surface of the partition are replaced by hot ones. With a condensable gas, condensation will take place on the surface of the partition and a film of the liquid will be formed. Due to the high resistance of such a liquid film to the passage of heat by convection or conduction, the transfer

(1) Transmission of Heat in Surface Condensation.  
Jrnl. Amer. Soc. M. E. 1910.

(2) Zeit. d. Ver. d. Ing. 1888 438.





will be reduced. If this liquid can be removed or the film thickness decreased, the transfer will not be lowered as much. Because of this fact it is to be expected that the tubes or plates placed in a position which facilitates the draining off of the liquid will transfer the greatest amount of heat. Hausbrand says that condensed steam drops off a horizontal pipe easier than it does from a vertical one.

(1)

Nichol experimented with tubes in which the heat was transferred from steam on the inside to water on the outside first in a horizontal and then in a vertical position. He found a greater transfer when the tubes were in a horizontal position. Hepburn takes issue with Nichol and believes that the condensed steam does not account for the differences of transfer as he points out that Nichol, in some cases, gets a greater transfer where the water film is supposedly thicker.

(3)

Kopp and Meystrie showed that the heat transferred is much larger with steam on the outside of a copper coil than it is with the steam inside, this being due in part

- (1) Effect of velocity of Water in Surface Condensation. Engineering 1875; 20; 449.
- (2) The Transfer of Heat from Steam to Water through a Partition. Power 1901; 21; p.18.
- (3) Transfer of Heat through Copper Coil from Steam to Water. Stevens Indicator. Jan. 1894.



to the fact that the condensing water when inside the coil flows over the surface more rapidly and because it is easiest to drain the condensed steam from the outer surface.

(1)

Stanton found an increase in the transfer with cooling water flowing down a tube over that of the water flowing up, although at high velocities the increase was not as much as at low velocities. Hepburn<sup>(2)</sup> says that the advantage is probably due to the increase of the velocity of the particles of the water in their descent through the tube due to the action of gravity. This leads to a gradual separation of the particles and a reduction of the friction between them and a consequent increase of the effect of the friction between the water and the tube surface. The decrease of the advantage as the velocity increases is due to the fact that the velocity due to gravity is proportionally less and less of the total velocity.

In addition to the effect of the condensed liquid film on the hot side of a partition the film (See Section I) on the cold side also exerts an influence on transfer. Classen<sup>(3)</sup> says that the transfer coefficient de-

(1) Heat Transfer in Tubes.

Proc. Inst. M. E. 1898 21 18

(2) Power 1901 21 18.

(3) Heat Transfer during Evaporation of Water and Aqueous Solutions. Zeit. d. Ver. d. Ing. 1905 46, p. 418.



creases with an increase of height of liquid on the heating surface, the reason being that there is a decrease of temperature difference due to the increase of boiling point at the surface. Holborn and Dittenberger<sup>(1)</sup> and Austin<sup>(2)</sup>, as already mentioned, in their measurements of the liquid film resistance, found that when the water is boiling the resistance is reduced and that the degree of reduction is dependent on the rate of boiling. It is then also possible that the hydrostatic pressure will influence the resistance of the film because of its effect on the rate of ebullition, and it is then to be expected that with a horizontal partition, where the hydrostatic pressure is uniform the transfer would not be equal to the transfer in a vertical partition where the pressure is not uniform.

<sup>(3)</sup>  
Anderson worked with sugar evaporators and found that the coefficient K with water was 1270 and with a sugar solution was 1070. Classen<sup>(4)</sup> says that in the

(1)	Zeit. d. Ver. d. Ing.	1900	44	1724
(2)	Ibid.	1902	46	1846
(3)	Proc. Inst. C. E.	1873	35	49
(4)	Zeit. d. Ver. Ing.	1905	46	418



vaporation of solutions the nature of the solute is of utmost importance. Salt solutions give the same or slightly higher coefficients than water under the same conditions while in a sugar solution the coefficient drops off with increasing concentration. All organic solutions, says Classen, might be taken to follow the same rule.

The presence of moisture in non-condensable gases, it has been found, increases the transfer and Stadler<sup>(1)</sup> for this reason recommends that the products of combustion of moist materials be used for evaporation. Air in steam on the other hand materially lessens the transfer. With steam the pressure, not the velocity, is the force which is continually bringing up the fresh particles to the partition to give up heat. Air in steam reduces its partial pressure and also takes up space which might be more efficiently occupied by live hot steam.<sup>(2)</sup> Smith gives the results of experiments with an admixture of air and steam and he finds that a partial pressure of air of

1/10"	reduces the transfer	25%
1/4"	" " "	40%
3/8"	" " "	50%

- (1) Notes on Theory and Practice of Evaporation;  
Jour. Frank. Inst. 166 291
- (2) Engineering. March 23, 1906.





(1)  
Orrok concludes from his experiments that the decrease of transfer due to air in steam is a function of the fifth root of the ratio of the partial pressure of steam to the total pressure. The fact that some of the earlier experimenters on heat transfer did not recognize the importance of the effect of air in the steam may account for certain discrepancies in their results.

(1) Jour. Amer. Soc. M. E. 1910.



Section 8.                    Influence of Velocity.

The marked increase of the coefficient of transfer with an increase of the velocity of the gases or liquids, has been noted by all experimenters but they do not all arrive at the same relation between the two factors.

(1)  
Halliday experimented with water passing through glass and metal tubes heated outside by steam or flames and found that the amount of heat absorbed by the water depends upon the rate of flow and that as the rate of flow increases the absorption first increases to a maximum and then diminishes, the critical rate of flow depending upon the nature of the heat and possibly also on the kind of motion which the water has in the tube. The quantitative relation of the heat supply to the heat absorption was not

(2)  
investigated. Halliday continued his investigations passing hot water through the tubes and measuring the evaporation. His conclusions in this experiment are that the quantity of water evaporated depends upon the quantity of heat supplied and secondly upon the speed at which the

- (1) Absorption of Heat by Water in Motion.  
Engineer 1898 87 473, and  
Engineer 1899 88 20

- (2) Influence of Velocity on Evaporation.  
Engineer 88 653



water flows through the tube.

(1)  
Joule after experimenting most carefully with a small vertical tube surrounded with flowing water and filled with air, concludes:--

"The conduction was nearly proportional to the cube root of the velocity of the water; but at very low velocities it evidently increases more rapidly than according to this law while at very high velocities it increases less and less rapidly as it gradually approaches a limit determined by the resistance of the metal and of the film of water adhering to the surface of the tube."

(2)  
Experiments of Ser show that in a horizontal tube the transfer is proportional to the cube root of the velocity of the water. Hageman, (3) with apparatus similar to Joules, except with the steam outside and the water inside, for small velocities of water got K proportional to the square root of the velocity but for higher velocities

(1) Experiments on the Transmission of Heat.  
Phil. Trans. Royal Soc. 1861.

(2) "Physique Industrille" I p. 225.

(3) Experiments on Condensation of Steam and the Influence of Water Velocity.  
Proc. Inst. C. E. 1884 77 311



it came nearer to being the cube root. Further experiments of Ser on the heat exchange between two liquids show it to be proportional to the square root of the velocity when the velocities of the two liquids are the same.

With air Joule found that the heat transferred is proportional to the square root of the velocity. Ser found the same relation for certain large tubes but not for small ones. For large tubes he got the transfer exactly proportional to the square root of the velocity. With small tubes, 10 to 50 m.m. in diameter, he noticed that at constant velocities the transfer was proportional to the tube diameters. Hausbrand mentions the flue gas experiments<sup>(1)</sup> in which the relation between the heat transferred and gas velocity was dependent on the square root of the velocity.<sup>(2)</sup> Richards also recommends the use of an equation containing the factor, square root of velocity:<sup>(3)</sup>

Orrok concludes that the transfer from steam to air is proportional to the square root of the water velocity and independent of the steam velocity, as has been stated

(1) Zeit. d. Ver. d. Ing. 1888 438

(2) "Metallurgical Calculations" Vol. I.

(3) Jour. Amer. Soc. M. E. 1910.





in Section 8. Ser thought that the same formula holds for steam as for water.

Joule had a spiral wire which could be slipped on the tube under test. He found the increase of transfer due to a mixing of the medium by the spiral to be 30 per cent for water and 30 to 40 per cent for air.



Section 9.                      Influence of Dirt, Oil, Scale, etc.

(1)

At the University of Illinois experiments were made on the transfer through boiler tubes before and after removing the accumulated scale. The results show that:

"(1) Considering scale of ordinary thickness, say up to 1/8 inch, the loss in heat transmission due to scale may vary in individual cases from insignificant amounts up to as much as 10 or 12 per cent.

"(2) The loss increases somewhat with the thickness of the scale.

"(3) The mechanical structure of the scale is of as much or more importance than the thickness in producing this loss.

"(4) Chemical composition, except in so far as it affects the structure of the scale, has no direct influence on its transmitting powers."

- (1) Conductivity of Boiler Scales. University of Illinois, Engineering Experiment Station, Bulletin #11.



(1)  
The experiments of the Reichenstalt with apparatus similar to Blechynden's, were also made with layers of artificial boiler scales and slime, of from five to eight m.m. in thickness, on the plates. The results show that the surface conditions on the water side of the plate do not change the transfer, even the effect of the scale and oil being hardly noticeable.

(2)  
Chamberlin found the transfer through cast iron plates was the same whether they were clean, painted with oil, or etched for a few days in acid, but that a plate etched and then painted with oil had its coefficient reduced 27 per cent.

(3)  
Sulzer found that a coat of lacquer decreased the transfer from a tube to water approximately 10 per cent.

(1) Bericht 1895.

(2) See Carpenter, Jour. Amer. Soc. M. E. 1891  
12, 174.

(3) See Mollier, Zeit. d. Ver. d. Ing. 1897  
41 153 & 197.



Section 10.

Influence of Temperature.

Many attempts have been made to couple the heat transfer with the temperature. It is generally said that the transfer is proportional to the temperature difference (1) between the media but Blechynden says that for certain dimensions the heat passing is proportional to the square of the temperature difference between the hot gases and the water so that

$$\frac{Q}{F \cdot Z (t_1 - t_2)^2} = \text{constant} = U$$

The results of the Reichenstalt (2) check this closely. (3)

In the transfer from steam to water Joule (4) and Rankine (5) take it proportional to the temperature difference. (6) Wemer Gashof and Weiso (7) proportional to the square and Orrok (8) proportional to the seven-eighths power.

Kopp and Meystrie show that the rate of trans-

- (1) Engineer 1893 II. 98
- (2) Bericht 1895
- (3) Phila. Trans. Royal Soc. 1861.
- (4) "Steam Engine".
- (5) Z. d. V. d. I. 26 394
- (6) See Orrok. T. A. S. M. E. 1910.
- (7) J. A. S. M. E. 1910.
- (8) Stevens Indicator Jan 1894.





fer per degree temperature difference increases with the temperature of the cooling water. Nichols<sup>(1)</sup> shows the same relation but Isherwood<sup>(2)</sup>, experimenting with a bronze cylinder immersed in steam, concludes that the temperature had very little effect on evaporation. Hepburn<sup>(3)</sup> says; "The absorption of heat per square foot of surface  $x \ x \ x$  is a constant for a given size and kind of tube at a given velocity. The 1908 catalogue of the American Radiator Company and the results of experiments by Billings<sup>(4)</sup> show that the heat transferred increases with the temperature difference between the steam and water.

(5) Clarks Manual mentions the work of Laurens and Thomas who submerged a coil of copper pipe, filled with steam in a vessel of water. From their data it is shown that over three times as much heat is transferred per degree temperature difference when the water was boiling than when it was being heated up.

- (1) Engineering 1875 20 499 .
- (2) Editorial Eng. Rec. March 5, 1898.
- (3) Power. December, 1901. 21 18.
- (4) Engineering Record. February, 1898.  
(Kent's Mechanical Engineer's Handbook.)
- (5) Kent.



(1)

Halliday compared the heat absorptive power of water below and above the boiling point and his apparatus was so arranged as to eliminate the effects of the circulation due to ebullition at the boiling point. He had the water flow upwards faster than the bubbles which were given off. It was found that there was a decrease of transfer after the water had reached the boiling point. The results are not expressed in units per temperature difference but at any rate they show that the coefficient of transfer derives more advantage from motion over the partition than from any new properties of the water at the boiling point.

(1) Engineer      1899      87      473.



Section 11.

Bibliography.

The articles in the following bibliography have been placed under the headings of--

- (1) Total Transfer (considered as one problem),
- (2) Films and the Transfer from a Partition to a Medium,
- (3) Conductivity Measurements and General Data,
- (4) Mathematical Formulae on Transmission and Transfer and the Effect of Scale and Velocity of Medium.

Some of the articles are of such a general nature that it was difficult to classify them exactly. These have been placed under heading (1). References of a scientific nature have been included with the idea that they might prove valuable if a more thorough study is made of the nature and characteristics of the film.

Dalby's "Heat Transmission", (Proc. Inst. M.E. 1909, p. 921) is the report of two years' work on the subject for the British Institution of Mechanical Engineers. Over 400 references on transmission are given and the article and discussion are exceptionally good. The transfer from hot gases to water is largely dwelt upon.

Mollier's work (Zeit. d. Ver. d. Ing., 1897, p. 153 and 197) is a similar report to the German Society



of Engineers. He discusses all the important work up to 1897. The article is somewhat mathematical and many coefficients are derived from the results of previous experiments.

Orrok's experiments were conducted on the transfer from steam to water and his article (Jour. Amer. Soc. M. E., 1910, advance copy) contains a complete bibliography on this phase of the transmission.

Neither Dalby's nor Orrok's article was available until this investigation was nearly completed.





Total Transfer Considered as One Problem.

- |      |           |  |
|------|-----------|--|
| 1844 | Peclet    | "Traite de le Chaleur".  |
| 1861 | Joule     | Experiments on the Transfer of Heat.<br>Phil. Trans. Royal Soc. 151 p.133                  |
| 1873 | Anderson  | Transfer in Sugar Evaporators.<br>Proc. Inst. C. E. 35 p. 49.                              |
| 1887 | Reynolds  | Influence of Air in Steam on Trans-<br>mission.<br>Zeit. d. Ver. d. Ing. 31 p.284.         |
| 1890 | Hudson    | Heating and Concentrating Liquids by<br>Steam.<br>Engineer, p. 291.                        |
| 1891 | Carpenter | Heat Transmission through Plates<br>treated with Acids.<br>Jour. Am. Soc. M. E. 12 p. 174. |
| 1891 | Royse     | Heat Transmission through Plates<br>treated with Acids.<br>Jour. Am. Soc. M. E. 12 p.1014. |
| 1892 | Morrison  | Transmission of Heat through Cast<br>Iron Walls.<br>Proc. Inst. M. E. p. 482.              |
| 1893 | Morrison  | Heat Transmission through Metal<br>Plates.<br>Engineer,                                    |



- 1894 Kopp & Meystrie Heat Transmission Experiments.  
Stevens Indicator, Jan.
- 1897 Kohlrausch Transfer Experiments with Plates.  
Engineering 63 p. 31.  
Zeit. für Instrumentenkunde,  
1897, p. 235.
- 1897 Blechynden Transmission of Heat through Plates  
to Water.  
Engineer, p. 509.
- 1897 Mollier Heat Transference and  
  
Zeit. d. Ver. d. Ing. 41  
p. 153 & 197.
- 1898 Editorial Transmission of Heat through Copper  
Coils.  
Eng. Record, March 5.
- 1898 Sadtler Theory and Practice of Evaporation.  
Journal Franklin Institute,  
166, p. 291.
- 1899 Halliday Absorption of Heat by Water in Mo-  
tion.  
Engineer 87, p. 473.  
Ibid. 88, p. 20.



- 1899 Halliday Transmission of Heat through Plates.  
Industries and Iron 24 p.487  
Ibid. 25 p.4
- 1899 Stanton Heat Transference in Tubes.  
Proc. Inst. C. E. 136 II.
- 1900 Hausbrand "Evaporating and Condensing Appara-  
tus.  
Translated from the German.
- 1901 Hepburn Transfer of Heat from Steam to Water  
through a Partition.  
Power, December.
- 1904 Fuchs Transmission of Heat in Various Parts  
of a Boiler Heating Surface.  
Zeit. d. Ver. d. Ing. 45 Mar.12
- 1905 Classen Heat Transfer during the Evaporation  
of Water and Aqueous Solu-  
tions.  
Zeit. d. Ver. d. Ing. 46 p.418
- 1906 Smith Experiments on the Effect of Air in  
Steam.  
Engineering Mar. 23.
- 1907 Billings Heat Absorption through Tubes.  
Engineer (U.S.) May 15.



- 1908     Miller            Circulation of Heated Liquors. .  
                         Jour. Soc. Chem. Ind. 28     3  
                         p. 125.
- 1909     Dalby             Heat Transmission.  
                         Proc. Inst. M. E.   p. 921.
- 1909     Jordan                Rate of Heat Transmission between  
                         Fluids and Metal Surfaces.  
                         Proc. Inst. M. E. 1909 p. 1317.
- 1910     Orrok                Transmission of Heat in Surface  
                         Condensation.  
                         Jour. Am. Soc. M. E.





### Films and the Transfer from a Partition to a Medium.

- |      |                           |  |
|------|---------------------------|--|
| 1856 | Boutigry                  | Spheroidal State of Water and Water<br>Film.<br>Proc. Inst. C. E. 15 p. 288.                         |
| 1897 | Sala                      | Temperature of Wires Traversed by a<br>Current.<br>Nuovo Cimento 6 p. 333.                           |
| 1897 | Stark                     | Spheroidal State.<br>Ann. Phys. Chem. 65.2.p.306.  |
| 1897 |                           | Temperature of Boiler Plates on the<br>Water side.<br>Proc. Inst. C. E. 132 p.274.                   |
| 1900 | Benard                    | Convection Currents in a Liquid Lay-<br>er.<br>Jour. d. Physique 9 p. 513.                           |
| 1900 | Holborn &<br>Dittenberger | Passage of Heat through Surfaces.<br>Zeit. d. Ver. d. Ing. 44 p.1724.                                |
| 1901 | Kempf-Hartman             | Heat Radiated from a Wire in a Vacuo.<br>Phys. Zeitschrift 3 p. 109.                                 |
| 1902 | Austin                    | Passage of Heat through Surfaces.<br>Zeit. d. Ver. d. Ing. 46 p. 1890.<br>Engineering, Jan. 1, 1904. |



- 1902 Mitchell Convection of Heat by Air Currents.  
Trans. Eng. Soc. of Edinburgh,  
40 1 p. 39.
- 1903 Rogovsky External Heat Conductivity of Silver Wires immersed in Water.  
Comptes Rendus 136 p. 1391.
- 1904 Beilby Effects of Heat and Solvents on Thin Films of Metals.  
Proc. Royal Society 72 p.226.
- 1904 Boussinesq Cooling Power of a Slightly Conducting Stream.  
Comptes Rendus 138 p. 1134.
- 1905 Rogovsky Difference in Temperature of Bodies in Contact.  
Comptes Rendus 140 p. 1179.
- 1905 Rogovsky Cooling of a Silver Wire Immersed in Water and Carrying Current.  
Comptes Rendus 141 p. 622..
- 1909 Kennely & Wright Convection of Heat from Small Copper Wires.  
Proc. Am. Inst. E. E. p. 699.



Conductivity Measurements and General Data.

- 1852 Despretz Conductivity of Metals and the Effect of Adding Salts to Water on its Conductivity.  
Comptes Rendus 35 p. 540.
- 1874 Milner & Chattock Thermal Conductivity of Water.  
Phil. Mag. 47 p. 46.
- 1876 Lees Thermal Conductivity of Mixtures and of their Constituents.  
Phil. Mag. 49 p. 286.
- 1895 Friedel Radiation through Liquids.  
Wied. Ann. 55 p. 453.
- 1896 Holborn & Wien Compilation of Conductivity Data.  
Zeit. d. Ver. d. Ing. 40 p.45.
- 1898 Lees Thermal Conductivity of Solid Salts.  
Manchester Lit and Phil. Soc.  
42 5 p. 1.
- 1898 Lees Measurement of Thermal Conductivity.  
Phil. Trans. 191 p. 399.
- 1899 Forsch Surface Tension of Aqueous Solutions.  
Wied. Ann. 68.4 p. 801.
- 1900 Kipp. Surface Tension of Water over 100°C.  
Phys. Review. 11 p. 129.



- 1901    Compan            Cooling Power and Conductivity of  
   Air.  
   Comptes Rendus    133    p. 1202.  
   Ibid.                    134    p. 522.
- 1902    Magie                Specific Heats of Solutions.  
   Phys. Review        15       p. 65.
- 1904    Leonard                Experiments on the Loss of Heat  
   from Iron Pipes.  
   Canadian Soc. C. E.    Oct.
- 1904    Weber                  Heat Conduction in Liquids.  
   Ann. d. Physik.    11    5    p. 1047
- 1905    Novell                 Sheet Metal Radiation.  
   Ann. Soc. Heating & Vent. Engs.  
   July.
- 1905    Vaillant                Specific Heat of Solutions of Copper  
   Sulfate.  
   Comptes Rendus    141    p. 658.
- 1905    Holborn & Wien        The Specific Heats of Gases at High  
   Temperatures.  
   Phys. Review II     p. 209.
- 1908    Smith                  Effect of Tension on Thermal and  
   Electrical Conductivity.  
   Phys. Review        27       p. 107.
- 1908    Allen                  Coefficients of Transmission in Cast  
   Iron Radiation.  
   Heat. & Vent. Aug. p. 20.





- 1909    Hoskin                    Viscosity of Water  
                                 Phil. Magazine.    p. 260.
- 1909    Hering                    Heat Conduction and Resistance of  
                                 Composite Bodies.  
                                 Electrochemical & Metallurgical  
                                 Industry,    p. 11.
- 1909    Dietz                    Heat Transmission Coefficients.  
                                 Gesundheits Ing.    March 20.



Mathematical Formulae on Transmission and Trans-  
mission and Transfer and the Effect of  
Scale and Velocity of the Medium

- 1875    Nichol                    Effect of Velocity of Water in  
   Surface Steam Condensing.  
   Engineering    20   p. 449.
- 1883    Werner                    Increase of Heat Transmission on  
   the Velocity and Dampness  
   of the Gases.  
   Zeit. d. Ver. d. Ing.    27   p.  
   394.
- 1883    Winkelmann                Dependence of the Coefficient of  
   Conductivity of Heat in  
   Gases on the Temperature.  
   Proc. Inst. C. E.    77   p. 468.
- 1883    Hagmann                    Experiments on the Condensation of  
   Steam and the Influence of  
   Water Velocity.  
   Proc. Inst. C. E.    77   p. 311.
- 1888                            Coefficient of Transmission  
   Zeit. d. Ver. d. Ing.    32   p.438
- 1899    Aberbeck                    Cooling Action of Currents of Air.  
   Wied. Ann.    56   p. 397.



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- 1902 Boiler Scale and the Transmission of Heat.  
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- 1907 Stanton Radiation Data for a Handbook.  
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Heat. & Ventilating, July.
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Elec. Rev. London, p. 784.



P A R T    I I .





Section 12.

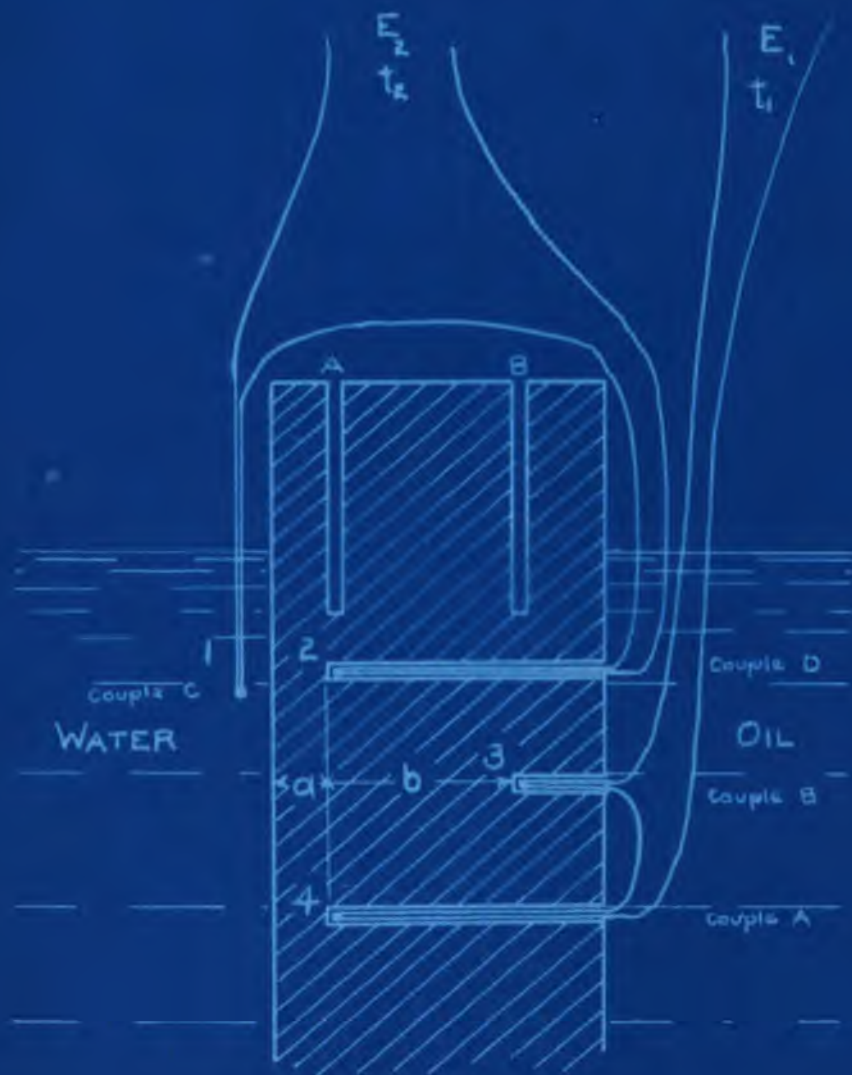
Kohlrausch Method of Measuring  
the Heat Passing through  
a Partition.

In almost all transfer experiments the heat passing through a partition has been measured by noting the change of temperature of either media and then computing the quantity of heat from thermal data. Where there is no flow of the medium this method is satisfactory, but where it is desired to keep the temperatures of the media constant it is not applicable. Professor Kohlrausch suggested a method of measuring the instantaneous heat passing in an indirect manner so that the change of temperature of either media will not enter into the calculations. His method is to measure the temperature drop in a known depth of the partition wall and then compute the heat flux knowing the coefficient of conductivity of the partition. Dr. Kohlrausch also extended his method to measure the temperature difference between the partition surface and the medium.

Plate II shows the cross-section of a partition fitted to make these measurements. The heat passes from the oil through the partition into the water and the temperature drop between the partition surface and the water is to be measured. Three holes, (2) (3) and (4) are



# PLATE II





drilled into the partition from the oil side, two almost through and the third just beneath the surface on the oil side. A thermocouple is placed in each hole and insulated from the partition. The junctions are placed way in and the couples then indicate the temperatures at the points (2) (3) and (4). As the temperature differences, only, are desired, the couples can be connected in pairs in opposition so that the difference in electromotive force can be read directly. (1) is a similar couple but it is placed in the water near the partition and is connected in opposition to (2). The potential  $E_1$  will then indicate the temperature difference between (3) and (4) and  $E_2$  the temperature difference between (2) and (3). If the distance between (3) and (4) is (b), and the distance between (4), (2) and the surface of the partition is (a), and if the temperature corresponding to  $E_1$  is  $t_1$ , then  $t_1 \times \frac{a}{b} = t$ , where (t) is the temperature difference between the partition surface and (2) (4).  $t_2$  is the temperature difference between the water as indicated by couple (1) and the temperature at (2) and corresponds to the potential  $E_2$ , hence  $t_2 - t = x$ , where x is the temperature difference between the surface of the partition and the water.



Section 13.      Investigations of the Reichenstalt  
on Heat Transfer Resistance.

Two series of investigations have been carried out by the German Reichenstalt on the measurement of heat transfer resistance from a partition to water using the Kohlrausch method. Holburn and Dittenberger used a red brass partition and Austin used a wrought iron one.

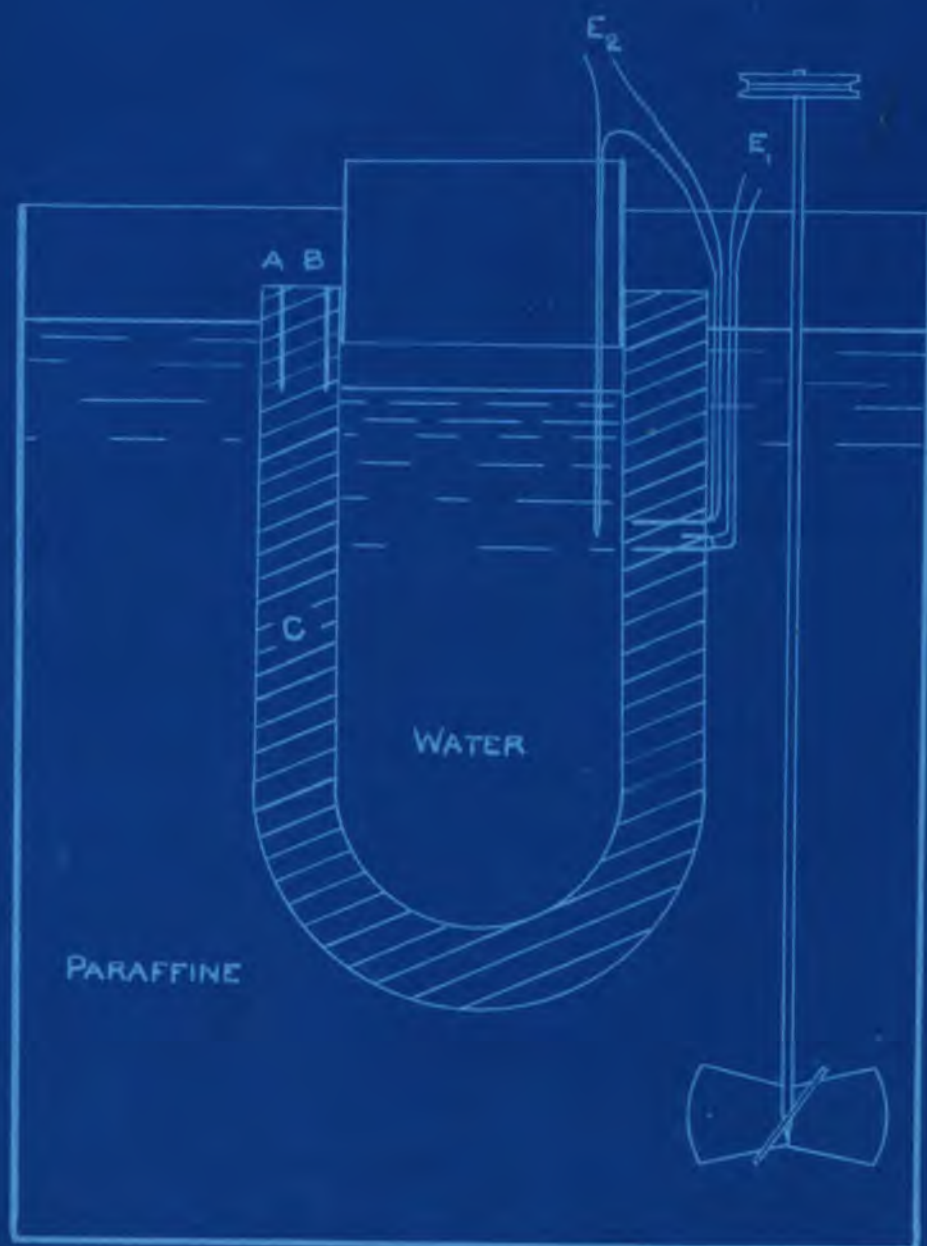
(1)  
Holburn and Dittenberger used an apparatus as shown on Plate III. The brass cylinder with a hemispherical bottom (C) is immersed in a paraffine bath which is heated by a gas flame. The cylinder is 2 cm. thick and 12.1 cm. outer diameter; a collar of sheet metal is brazed on the mouth and to prevent the water spattering into the paraffine. The outer bath is stirred and it was noticed that the temperature of the paraffine depended on the rate of stirring. The highest temperature reached was 155° and the temperature of the outer surface was then 107° ; revolutions of the stirrer 152 per minute.

The temperatures in the cylinder partition were measured with iron constantan couples of 0.1 mm. wires, placed in 0.5 m.m. holes. They were insulated with silk and the cold junctions kept at 0°C. Couple 1 (Plate II)

(1) Zeit. d. Ver. d. Ing. 1900 p. 1724.









was encased in a glass tube and it was found that its position in the water, relative to the inner surface, had no effect on the readings. At the beginning the position of (3) was near the outer surface, but it was found that it was too sensitive to fluctuations of the paraffine temperature. The final arrangement which was found satisfactory was to place it in about 4 m.m.

In order to determine whether the flow of heat was uniform through the wall, the two holes (A) and (B) (Plates II and III) were drilled in the cylinder parallel to the walls and the temperature difference measured with the couples in these holes. The results show that there is no appreciable change between the readings taken here and those taken in the holes (2) or (4) and (3).

The electromotive forces were measured with a potentiometer and the couples were calibrated against standard thermometers. Between  $100^{\circ}$  and  $115^{\circ}$  the voltage difference was 56.2 millivolts per degree and between  $0^{\circ}$  and  $100^{\circ}$  it was 54.7 millivolts per degree.

The quantity of heat flowing through the wall was computed from the data using  $0.169^{(1)}$  gram cal. c.g.s. units as the conductivity of the brass. The method of

(1) Jager & Disselhorst. *Sitzungsber. der Berl. Akad.* 1899 II, p. 746.



taking readings was to take  $E_1$ , then  $E_2$ , and then  $E_1$  again. The revolutions per minute of the stirrer were noted at the same time. The average of the  $E_1$  readings was used in the computations.

Because of the shape of the partition the formula for calculating the temperature difference ( $t$ ) (page 57) was somewhat involved, and takes the form of

$$t_2 = \frac{t_3 - t_4}{\log_e \frac{r_3}{r_4}} \log_e \frac{r_4}{r_3}$$

where  $t_3$  and  $t_4$  are the temperatures measured at the radii  $r_3$  and  $r_4$ ; and  $r_2$  is the radius of the junction (2)

From four runs with the water boiling the investigators derive the expression

$$x = 0.782 + 3.68 Q$$

where  $Q$  is the number of gram calories passing per sq. cm. per sec.

If the value of  $Q$  is equal to the quotient of the temperature difference  $x$  and  $R$  the heat resistance of a unit section of the film,

$$R = \frac{x}{Q}$$

Taking  $R$  for brass as .169, then  $y$  the equiva-



lent thickness of a sheet of brass having the same resistance is

$$y = 0.622 + \frac{0.132}{Q} \text{ cm.}$$

If R for iron is .145, for iron

$$y = 0.534 + \frac{0.113}{Q} \text{ cm..}$$

Hence it is seen that if Q can be increased enough, conditions may be reached where the resistance is equivalent to a minimum of 0.622 and 0.534 respectively for iron and brass.

Experiments were conducted with the heat flowing from the boiling water to oil at 70°. It was found that the equation for the equivalent iron thickness in this case is

$$y = 0.458 + 1.91Q$$

It is seen that when Q is zero the equivalent y is almost the same in both cases.

(1)

Mr. L. Austin worked on the transfer resistance from a wrought iron partition to water using the Kohlrausch method. His apparatus was decidedly different than that of Holborn and Dittenberger's in that the partition was a flat plate 3 cm. thick between two chambers, one containing the hot oil and the other water. The water chamber was covered and an upright condenser served to con-

(1) Zeit. d. Ver. d. Ing. 1902 46 p. 1860.





dense the steam which flowed back into the bath. Heat was applied by bunsen burners and both baths were stirred. The water chamber contained a copper cooling coil by means of which the water could be kept at temperatures below boiling. (See Plate VI for cross-section of an apparatus very similar to Austin's.)

In Austin's apparatus the conditions of temperature and stirring on either side of the partition could be regulated and held constant. This was impossible in the apparatus of Holburn and Dittenberger except with the water at boiling. By passing water through the cooling coil and increasing the temperature of the oil bath the temperature drop through the plate could be held high and by decreasing the oil temperature and increasing the water temperature this difference could be made smaller. Austin helped and sometimes accelerated the boiling by placing additional burners under the water compartment. The degree of boiling was indicated by the height of the condensate in the condenser.

The holes in the plate were 2.5 and 1.5 cm. deep by 1 m.m. diameter. Iron constantan couples were used and they were held in the holes by wooden plugs. The cold junctions were kept at 0° and the potentials measured by a potentiometer.



Determinations were made noting the effect of stirring on the ratio  $\frac{x}{g}$  at 30°, 90° and 100°.  $g$  is the heat gradient per centimeter through the plate.

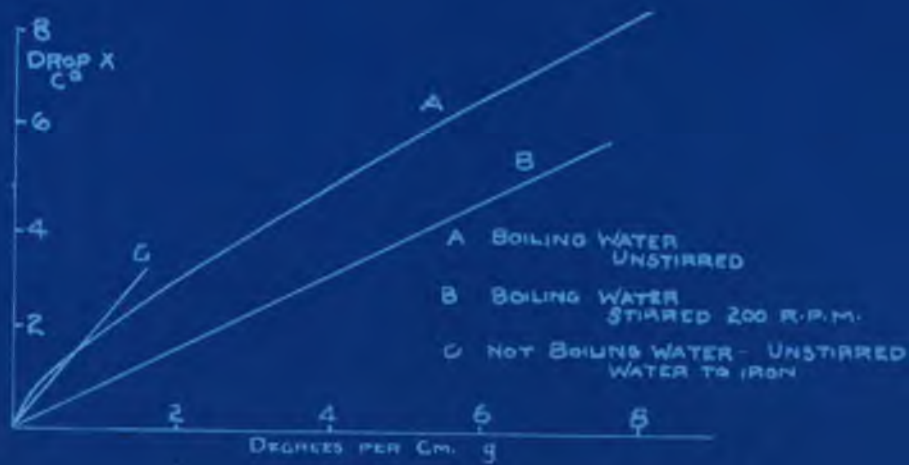
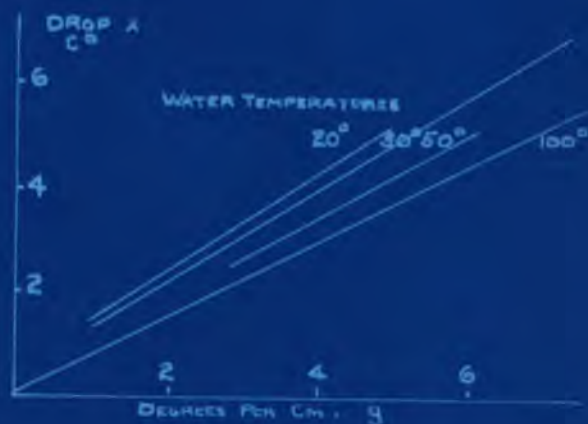
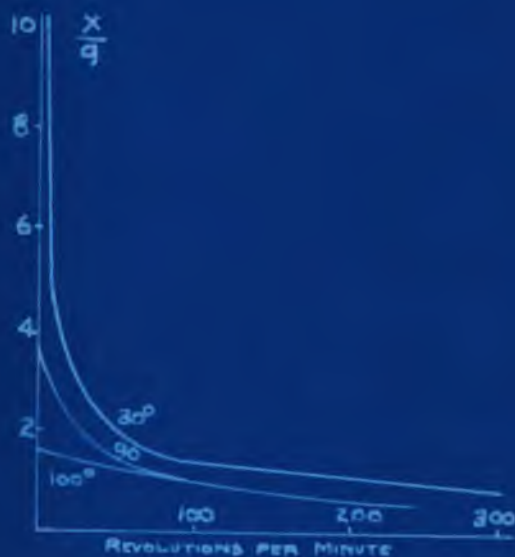
It was found that the curves for 30° and 90° fall off suddenly but that after about 140 R. P. M. of the stirrer they lie close together, almost parallel and with only a slight slope. (See Plate IV, Fig. 1.) The curves for 90° and 100° unite at about 90 R. P. M. At 140 R.P.M. the ratio of degrees per revolution was found by Austin to be 0.0016 and this value was used to correct some of the readings to bring them to constant R. P. M. The effect of the stirring caused by the boiling of the water is strikingly shown on the curve by the lesser value of  $\frac{x}{g}$  at no R. P. M.

Curve 2, Plate IV, shows the graphical result of a test made on water below boiling and stirred at 200 R. P. M. The ratio  $\frac{x}{g}$  is about the same for the same temperature but decreases with an increase of temperature. Austin finds the following:-

Temperature of water	$\frac{x}{g}$
20°	1.19
30°	.94
50°	.83
100°	.76



# PLATE III





This rate of falling off, says Austin, is comparable to the  
(1)  
viscosity of water as noted by Stanton.

The 100° curve passes through zero which means that at zero the temperature difference inside the partition (x) would be zero, that is there would be no resistance to the transfer at the surface.

Holborn and Dittenberger did not stir the water at boiling and from their equation for (x) (page 60) it would have some finite value even when Q, (which is directly proportional to g) is zero. The results of Austin as plotted by him are shown by curve A, Fig. 3, Plate IIII. He gives the curve a dip at  $g = 1$ , and has it pass through zero although from the data it would be seen that the curve ought to cut  $g = 0$  at  $x = 3.5$ . Plate V shows the points given by Austin and the curve as it would appear to be correctly drawn. The equation for this curve would be of the form

$$y = a + b x$$

which is similar to the form of Holborn and Dittenberger's (page 61) for the same conditions, viz., boiling unstirred.

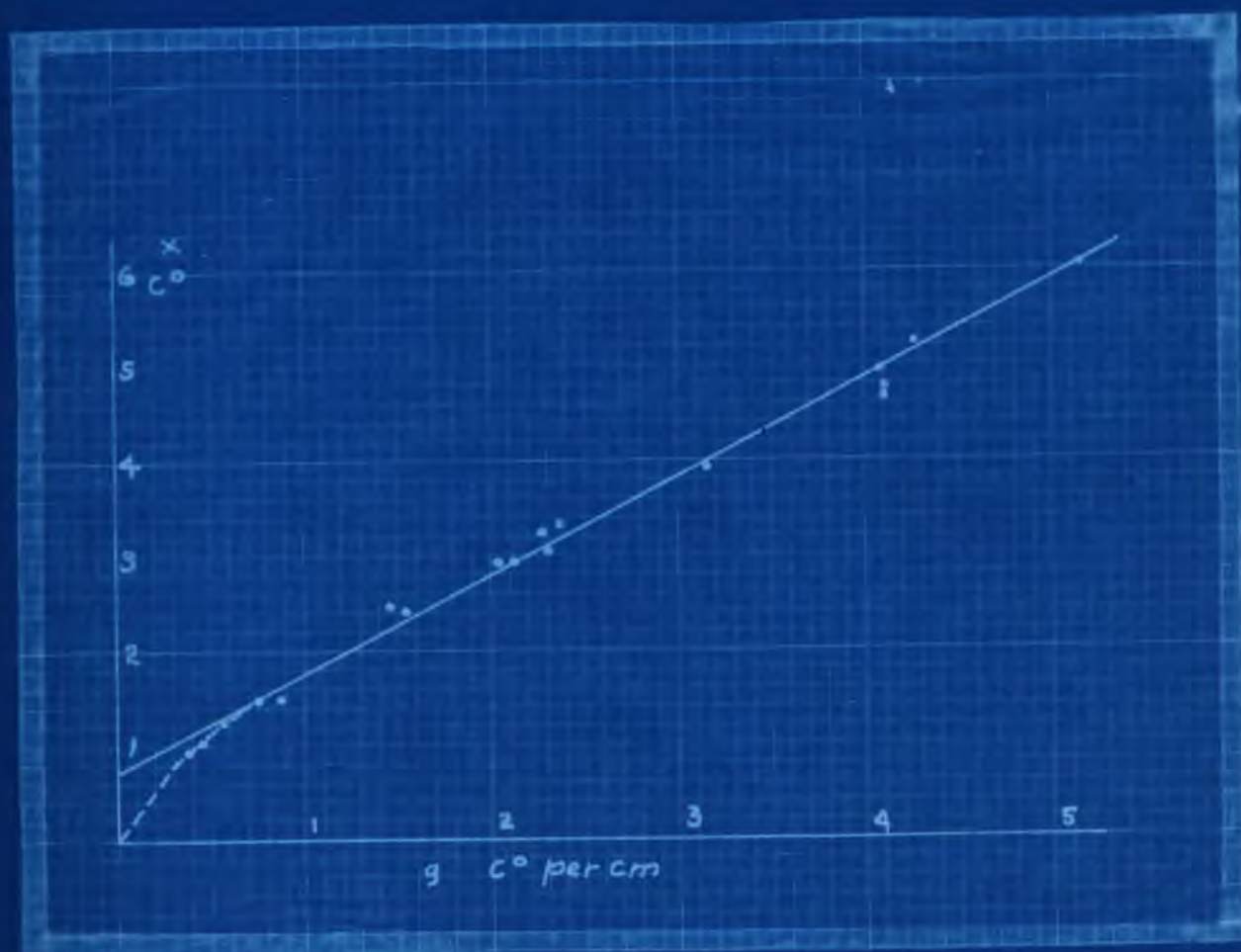
For rapidly boiling water stirred it was noted that  $\frac{x}{g}$  was higher than for slight boiling. It is also

(1) Phil. Trans. Royal Soc. 1897 190 II p.67





# PLATE V





lower for stirred than for unstirred water. Austin computes the equivalent thickness of iron ( $y$ ) correspondingly to  $x$  to be 0.76 cm. in unstirred boiling water and for  $g = 5$ ,  $y = 1.17$  cm. in unstirred. Hence by stirring at 200 R. P. M. the transfer resistance is lowered about one-third.

Austin tried to remove or decrease the film with revolving wire brushes but was unsuccessful and for this reason it was not mentioned in his report.<sup>(1)</sup> He found that water takes up rust but that the results are not affected.

His conclusions and results are--

(1) In unstirred boiling water the transfer resistance is equivalent to from 1.2 to 2 cm. of iron.

(2) Stirring reduces this to .75 cm. iron.

(3) With constant stirring the heat passing is proportional to the difference of temperature and the resistance is independent of the quantity of heat for boiling water.

(4) With water below boiling and unstirred the transfer resistance is equivalent to about 10 cm. iron. Stirring reduces it below 1 cm.

(1) Communicated to editor of Engineer.

Engineer Jan. 1, 1904.



(5) With constant stirring under boiling the resistance increases with a decrease of temperature of the water.

(6) From water to iron, unstirred the transfer resistance is constant and larger than in the reverse.

(7) In case (6) when stirred and boiling the transfer resistance is the same.

(8) If the transfer resistance is due to a film of water it must be about 0.1 m.m. in thickness.



Section 14a.

Investigation of the Heat

Transfer Resistance from a

Cast Iron Partition to

Various Solutions.

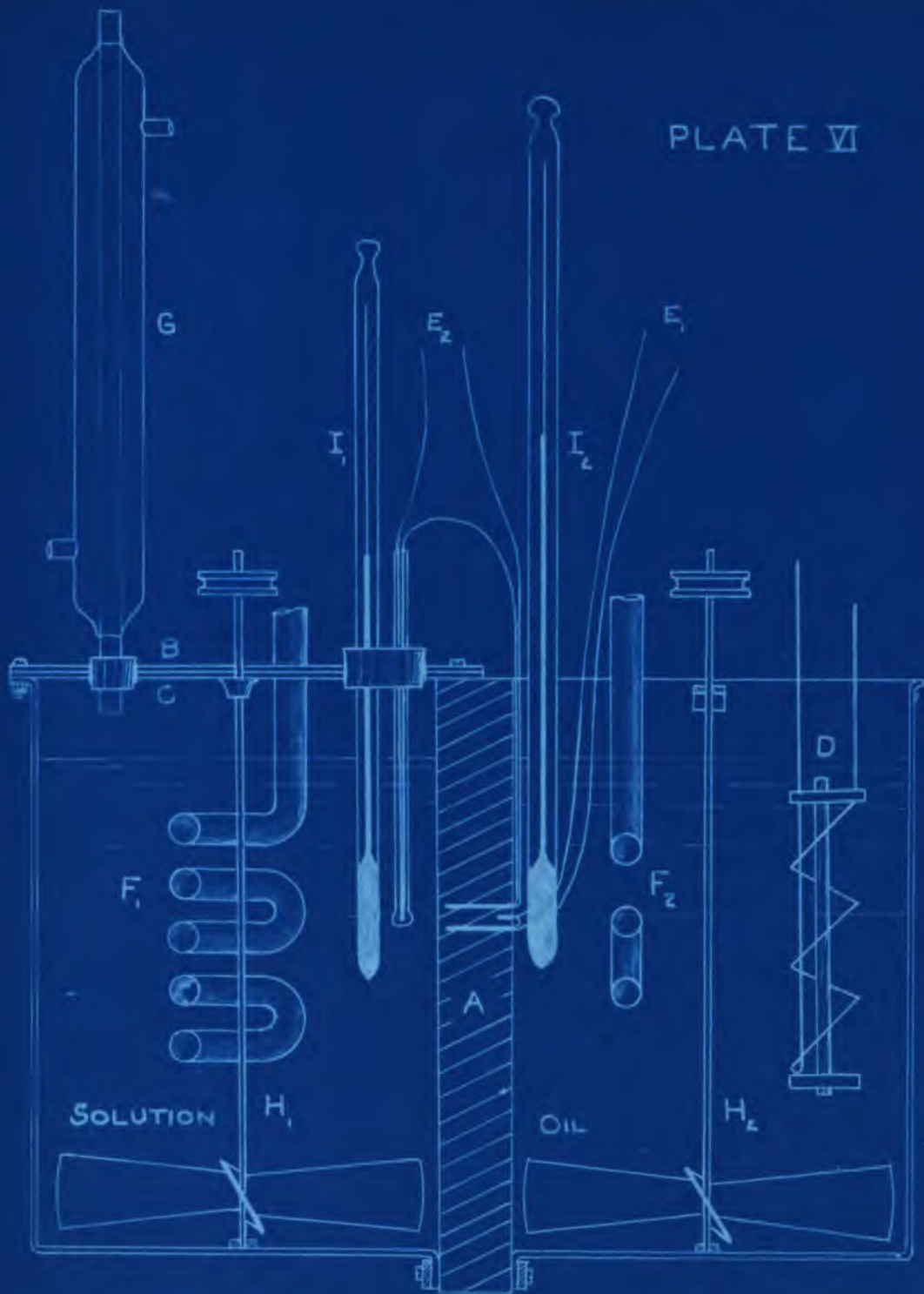
It has been noted that when a hot soldering iron is dipped into various solutions the sizzling noise and steam evolution is not the same in all cases. The reason for this has been ascribed to the heat transfer resistance which might not be the same for all solutions. The power of the solution to cling to a metal surface; the so-called wetting effect; it was thought might also effect the heat transfer. If such is the case there may be a relation between the film resistance and some other properties of the solutions such as the ease with which metals deposit out electrolytically, electrical conductivity, molecular weights, etc. As no direct measurements of film resistance into solutions have been made it was deemed profitable to copy Austin's apparatus and duplicate some of his experiments using different solutions in addition to water.

His apparatus was closely copied; the only extreme difference being that the heating was done by an electric heating coil instead of gas burners. Plate VI shows a cross-section of the apparatus. The cast iron plate A





# PLATE VI





is 29 m.m. in thickness and about 12 inches square and the three holes (2) (3) and (4) (Plate II) are drilled in the center of the face. These holes are placed at the vertices of an equilateral triangle about 2 cm. on a side. (3) is above the plane of (2) and (4). The diameters of the holes are 1 m. and their depths 24.5 m.m. and 6.0 m.m. respectively.

The surfaces of the plate are planed. A galvanized iron chamber of semicircular cross-section and 10 inches wide and 10 inches high is screwed on the plate on each side, the joint being made tight with a rubber gasket. The water chamber is closed by a cover (B) which is bolted down. (C) is the rubber gasket on the under side of the cover. (D) is the heater consisting of about 8 feet of Nichrome<sup>#21</sup> wire (Driver-Harris Wire Company) wound on a glass and mica frame and immersed in the oil. This heater is connected to 110 volt circuit with a lamp bank in series as control. ( $F_1$ ) and ( $F_2$ ) are the two copper cooling coils in the water and oil baths and (G) is the upright condenser to prevent loss of the steam formed. ( $H_1$ ) and ( $H_2$ ) are two stirrers with four blades each, about 4-1/4 inches long. Stirrer ( $H_1$ ) has a collar on the shaft which presses against a thin plate on the under side of the gasket thus making a simple tight joint



which serves the purpose of a stuffing box. Couple (1) is placed in a sealed glass tube, the end of which is blown out thin, next to the thermometer  $I_1$ , and is just opposite the thermocouples inside the plate.  $I_2$  is a thermometer in the oil bath. An "S" shaped glass tube not shown in the diagram serves the double purpose of a solution level gauge and a syphon to drain the chamber. The stirrers are driven by separate 10 v. D. C. motors through speed changing pulleys. The motor speed is regulated by varying the voltage.

The couples are of copper constantan and the method of calibration and the curves are given in appendix. Couple (A) is in hole (4), (B) in (3), (C) in the glass tube (1) and (D) in hole (2). The couples, when insulated by a wrapping of silk thread were just small enough to fit into the holes snugly. A disc of paper was shoved into the end of each hole so that the thermocouple junction would not touch the metal walls and the couples sealed in with sealing wax. The constantan wires were led out and the proper pairs spliced together above the surface of the oil. The copper wires, connected to the cold junctions, were led to the potentiometer.

The average thermocouple bead diameter was taken as about 1 m.m. Then the distances of the centers of



the junctions from the oil surface are 24.0, 5.5, and 24.0 m.m. for couples (D), (B) and (A) respectively. The plate thickness being 29 m.m.,

$$\frac{29.0 - 24.0}{24.0 - 5.5} = \frac{5}{18.5} = .27 \quad \text{represents the}$$

ratio  $\frac{a}{b}$  (page 57. ).

The two sets of couples  $E_1$  and  $E_2$  were connected to the same potentiometer, with the same standard cell, by which they were calibrated through a double throw, double pole switch so that either potential could be measured. The same ice bath was also used for the cold junctions.

The temperature differences,  $t_1$  and  $t_2$  were found from the calibration curves after the potentials  $E_1$  and  $E_2$  were known. To do this, however, two conditions had to be assumed, namely:-- (1), that the temperature of couple (C) was the same as that indicated by the thermometer  $I_1$  and (2), that the temperatures of couples (D) and (A) were the same. The right to make the first assumption is based on the fact that  $I_1$  is the same thermometer (see appendix) against which couple (C) was calibrated and it is about the same distance from the couple as it was when calibrated. The second condition may be assumed as





Holburn and Dittenberger found the heat flow to be the same in parallel planes.

The calibration curves of the couples must have been either parallel straight lines or else all the couples had the same shaped curve, so that the potential differences could be converted into temperature differences directly without any troublesome measuring of the curves. The curves for the couples used are neither straight lines nor alike, as the data in the appendix shows. If the curves were called straight between  $90^{\circ}$  and  $135^{\circ}$  the error at  $100^{\circ}$  would be  $.75^{\circ}$  which would not be allowable.

The method of finding the temperatures of the separate couples from the curves was as follows:-- As the potential reading  $E_a$  gives the difference between couples (C) and (D) and as (C) is at the lower temperature then the temperature of (D) is the temperature, on the curve of (D), corresponding to  $E_c + E_a$  millivolts where  $E_c$  is the millivolts corresponding to the temperature of (C) on (C) curve. The temperature of (A) is the same as (D) so the temperature of (B) is found in a similar manner after knowing  $E_1$  the potential difference between A and B. The  $65^{\circ} - 135^{\circ}$  part of the curves were drawn on a scale of 4 inches per millivolt and 1 inch per 5 degree and the desired temperatures could be picked off from this large curve by the



aid of dividers and scale with a degree of accuracy close enough for the purpose.<sup>(1)</sup>

Plate VII shows a photograph of the apparatus as set up. The chambers are shown with a heat insulation consisting of a thin cotton quilt. This was later replaced by a layer of fossil flour 1-1/2 inch thick around and beneath the whole apparatus. The water compartment was also covered with asbestos cloth.

(1) See Appendix for a copy of this curve.



PLATE VII



galvanometer    lamp bank

speed changers

potentiometer

ice bath

APPARATUS



Section 14b.

Experimental Data.

It was found that when the temperature differences between the oil and solution were not over about  
(1)  
50° little trouble was experienced in keeping the temperatures fairly constant. This was done by regulating the current in the oil heater and the flow of water in the coil in the solution chamber. The water passed through a valve in which good regulation could be secured. When the temperature difference became large, it was found difficult to keep the temperatures stationary as it was hard to regulate the cooling water to carry away the exact quantity of heat necessary. With the oil at about 135° and the water at about 85° the rate of change of temperature of each could be kept as low as a fifth of a degree per minute either increasing or decreasing. Both baths were however seldom at the desired temperatures at the same instant but readings were made when the conditions were best. It is only the exceptional reading which shows a deviation of more than 0.5° either above or below the desired temperature.

The number of revolutions of the stirrers were measured by a speedmeter held on the stirrer shaft for 30 seconds but the data gives the speed in revolutions per minute.

(1) Centigrade degrees used throughout.





The order of taking the data is as follows:-  
When the temperature and speed seemed satisfactory  $E_1$  was read on the potentiometer and the switch then thrown to connect  $E_2$ . The potentiometer was then balanced, the two temperatures noted and  $E_2$  then read on the potentiometer. A second reading of  $E_1$  was then made and the speeds noted. It was desired to get the value  $E_2$  and the temperatures at the same instant. The two values of  $E_1$  are combined to give the average value which is tabulated in the data sheets. Thermometer  $I_1$  is a Dr. Siebert and Kühn certified  $0^\circ - 105^\circ$ , graduated to half degrees and readable to  $0.05^\circ$  with a magnifying glass. There are about  $30^\circ$  per 2 inches.  $I_2$  is a thermometer of the same make but not certified. It is graduated to degrees and readable to tenths. Its scale is  $0 - 250^\circ$ .



Section 14c.

Data and Results.

The following tables give the experimental data and the computed values for  $\frac{x}{t}$  ( $x$  is the temperature difference between the plate and<sup>1</sup> the solution) and  $t_1$  is the temperature drop in 18.5 <sup>mm.</sup> of the plate. (See Plate II.)

Column (1)	average of two $E_1$	, on potentiometer.
" (2)	$E$	" "
" (3)	Temperature of B	from curve.
" (4)	"	" A or D " "
" (5)	"	" C read on thermometer.
" (6)	"	" oil.
" (7)	R. P. M. of solution stirrer, $H_s$	.
" (8)	Temperature difference between (4) and (5)	
" (9)	"	" " (3) " (4)
" (10)	$t_1$ ((column (9) ))	multiplied by .27
" (11)	Temperature difference between (8) and (10)	
" (12)	Ratio of columns (11) to (9).	

Run 1.

This was made on water at about 70° in order to see what influence the stirring would have on  $\frac{x}{t}$ . As has been said, it was difficult to keep both the <sup>1</sup> oil and



water at the proper temperatures. The ratios  $\frac{x}{t}$  decrease, with an increase of stirring. No relation, <sup>1</sup> however, can be drawn between the two, except that above 100 R.P.M. the ratio is more nearly constant. The fact that there was difficulty in keeping the temperatures constant and that this was the first run, may account for the wide variation in values of  $\frac{x}{t}$ .

When it became apparent that stirring seemed to increase the ratio of  $\frac{x}{t}$  at boiling in run 5 with sodium hydrate, the direction of stirring was reversed. The ratio decreased somewhat but did not equal the value obtained at no stirring. It will be noticed that in the tests where no stirring took place ( $x$ ) has a negative value. This of course is impossible, but may be due to one of the couples being out of place, or to a change in the calibration of the same. Since the couples were not disturbed throughout the entire set of experiments, the negative values do not affect the comparison of results.

The apparatus was first covered with a quilt and it appeared that too much radiation took place. Runs (6) (7) and (8) were made with the apparatus insulated by a layer of fossil flour. If the stirring would increase the radiation losses from the sides of the compartment it seemed that better insulation would prevent it. In all the



runs with the new insulation, negative values were obtained for (x), which means that the temperature of the solution was nearer that of the plate.

Run 6 shows that stirring does not reduce the difference (x) but increases it. At 85° (x) is the largest.

Run 7 with sugar shows that the temperature difference is greater than with sodium hydrate. (See Run 5).

Run 8 made with sodium sulfate was limited to boiling unstirred, and shows that here the temperature drop is about the same as in the sodium hydrate solution.

From the few experiments made, with this apparatus it may be said that:-

(1) Decrease of heat loss by radiation increases the transfer, or decreases the transfer resistance.

(2) The nature of the solution plays a part in the transfer resistance; for sodium hydrate and sulfate it is less than for water; for salt and sugar it is greater than for water.

(3) Concentration of the solution only affects the transfer at temperatures below boiling. For a salt solution it decreases with dilution.

(4) At boiling, stirring reduces the heat trans-





ferred. Below boiling stirring increases the heat transferred.



RUN 1. TABLE I.

Water

Oil		R.P.M.		150									
1	2	3	4	5	6	7	8	9	10	11	12		
Millivolts		Temperatures				RPM		Temperature		Diffs.			
E <sub>1</sub>	E <sub>2</sub>	B	A or	C &	Oil	of	t	t	t	x	x		
av.			D	Sol.		Sol	s	1	tx.27	t - t	t		
									1	s	1		
.489	.293	87.75	76.7	70.3	105.5	0	6.4	11.05	2799	3.41	.309		
.489	.273	87.25	76.05	70.3	104.0	0	5.65	11.2	3.03	2.52	.225		
.496	.250	86.60	75.2	70.0	104.0	83	5.2	11.4	3.08	2.12	.187		
.442	.245	85.5	75.3	70.25	104.0	84	5.05	10.2	2.75	2.75	.260		
.493	.256	86.5	75.3	70.0	104.0	90	5.3	11.2	3.03	1.27	.113		
.562	.238	88.00	75.3	70.2	106.0	164	5.1	12.7	3.43	1.67	.131		
.529	.233	87.25	75.25	70.2	103.5	168	5.05	12.0	3.24	1.81	.151		
.517	.227	86.05	74.4	69.7	104.1	216	5.3	11.55	3.12	1.18	.102		
.513	.223	86.05	74.3	69.7	104.0	216	4.7	11.65	3.15	1.55	.133		
.526	.220	85.90	73.95	69.4	104.0	230	3.55	11.95	3.23	0.52	.027		
.511	.212	85.6	74.05	69.8	103.6	252	4.15	10.55	2.85	2.40	.227		
.573	.211	85.3	73.7	69.25	103.8	338	3.45	11.6	3.86	-0.59			
.551	.212	85.6	74.0	69.6	105.0	342	4.4	11.6	3.86	0.54	.046		
.543	.215	85.05	74.0	69.5	104.8	335	4.5	11.05	2.95	1.55	.140		



RUN 2. TABLE II.

Water

Oil R.P.M. 150

1	2	3	4	5	6	7	8	9	10	11	12	
Milivolts		Temperatures				RPM	Temperature Dif-					
E <sub>1</sub>	E <sub>2</sub>	B	A or D	C & Sol	Oil	of Sol	t <sub>2</sub>	t <sub>1</sub>	t <sub>1</sub>	$\frac{x}{t_1}$	$\frac{x}{t_2}$	av.

70° - stirred

1.088	.391	102.4	77.8	69.2	135.6	262	8.6	24.6	6.58	2.02	.821	
1.062	.363	101.6	77.4	69.6	134.1	266	7.8	24.2	6.53	1.28	.530	
1.064	.365	101.3	77.5	69.75	134.8	304	7.75	23.8	6.42	1.33	.558	
1.052	.365	100.95	77.3	69.4	134.0	304	7.9	23.65	6.39	1.51	.638	
1.040	.356	100.8	77.25	69.6	133.8	309	7.55	23.55	6.37	1.18	.503	.610

Boiling - unstirred

.576	.253	115.4	103.2	99.1	135.6	0	4.1	12.2	3.29	0.81	.066	
.565	.260	114.8	103.1	99.1	135.2	0	4.0	11.7	3.16	0.84	.072	
.564	.270	115.6	103.8	99.1	135.4	0	4.7	11.8	3.19	1.51	.128	
.546	.277	115.0	103.8	99.1	134.9	0	4.7	11.2	3.02	1.68	.150	
.529	.274	114.8	103.6	99.1	134.8	0	4.5	11.2	3.02	1.48	.132	.091

Boiling- stirred

.527	.270	114.75	103.6	99.2	134.1	284	4.4	11.15	3.01	1.39	.125	
.502	.272	114.10	103.7	99.2	134.0	284	4.3	10.3	2.78	1.52	.197	
.500	.286	114.8	104.0	99.2	134.5	284	4.8	10.2	2.75	2.05	.201	
.496	.267	113.8	103.4	99.2	133.7	-	4.2	10.4	2.80	1.4	.135	
.488	.265	113.8	103.5	99.2	134.0	250	4.3	10.3	2.78	1.52	.147	.151

85° - stirred

.453	.344	108.0	91.5	85.0	134.5	220	6.5	16.5	4.45	2.05	.124	
.760	.343	108.5	91.6	85.1	134.3	240	6.5	16.9	4.56	1.94	.115	
.758	.338	107.8	91.2	84.9	134.2	250	6.3	16.6	4.48	1.82	.111	
.764	.337	108.2	91.3	85.0	134.3	270	6.3	19.9	4.56	1.74	.103	.111



RUN 3. TABLE III.

Sodium Chloride 58.5 grams per liter.

Oil R.P.M. 150

1	2	3	4	5	6	7	8	9	10	11	12
Millivolts			Temperature		Oil	RPM of Sol	$t_s$	Temperature dif- ferences			
$E_1$	$E_2$	B	A or D	C & Sol				$t_1$	$t$	$x$	$\bar{x}$
av.									$t_{x.27}$	$t - t_s$	$t_1$

Boiling - unstirred

.512	.285	115.0	104.3	99.65	134.3	0	4.65	10.7	2.89	1.76	.164
.495	.294	114.7	104.5	99.65	133.7	0	4.85	10.2	2.75	2.10	.206
.476	.285	114.4	104.3	99.65	134.1	0	4.65	10.1	2.73	1.92	.190
.495	.283	114.5	104.25	99.65	134.0	0	4.60	10.25	2.77	1.83	.178
.482	.281	114.3	104.1	99.65	134.0	0	4.45	10.2	2.75	1.70	.167
.489	.283	114.5	104.25	99.65	134.0	0	4.60	10.25	2.77	1.83	.178
.492	.278	114.3	104.1	99.65	133.9	0	4.45	10.2	2.75	1.70	.167
-- average						.178	---				

Boiling - stirred

.492	.310	115.05	104.8	99.7	135.3	300	5.1	10.15	2.74	2.36	.232
.500	.305	115.15	104.7	99.7	135.3	290	5.0	10.35	2.80	2.2	.212
.492	.305	115.0	104.7	99.7	135.0	282	5.0	10.3	2.78	2.22	.216
.483	.298	114.5	104.4	99.7	134.2	302	4.7	10.1	2.73	1.97	.195
.476	.297	114.4	104.4	99.7	134.0	296	4.7	10.0	2.70	2.0	.270
.485	.297	114.55	104.4	99.7	134.1	294	4.7	10.15	2.74	1.96	.270
.483	.285	114.45	104.3	99.7	133.8	287	4.6	10.15	2.74	1.86	.270
-- average						.238	--				

85° - stirred

.626	.357	105.6	91.7	85.0	133.8	315	6.7	13.9	3.75	2.95	.212
.634	.357	105.7	91.65	84.95	133.8	320	6.60	14.05	3.80	2.8	.199
.631	.359	106.0	91.9	85.0	133.9	330	6.9	14.1	3.81	3.09	.219
.634	.349	105.4	91.5	84.9	133.5	340	6.6	13.9	3.75	2.85	.212
.650	.360	106.5	92.0	85.2	135.0	312	7.2	14.5	3.92	3.28	.196
.625	.354	105.7	91.8	85.1	133.8	303	6.7	13.9	3.75	2.95	.212
.620	.352	105.4	91.8	85.25	134.0	288	6.55	13.6	3.67	2.88	.212
-- average						.209					





# RUN 4. TABLE IV.

Sodium Chloride 117.0 grams per liter.

Oil R.P.M. 150.

1	2	3	4	5	6	7	8	9	10	11	12
Milivolts			Temperatures			RPM	Temperature dif-				
E <sub>1</sub>	E <sub>2</sub>	B	A or D	C & Sol	Oil	of Sol	t	t	t	x	$\frac{x}{t}$
av.							s	i	t x.27	t - t	i
<u>Boiling - unstirred</u>											
.517	.290	116.3	105.6	100.8	133.8	0	4.8	10.7	2.89	1.91	.178
.515	.296	116.4	105.7	100.8	134.0	0	4.9	10.7	2.89	2.01	.187
.515	.288	116.2	105.55	100.8	133.7	0	4.75	10.65	2.88	1.87	.175
.512	.295	116.1	105.7	100.8	133.9	0	4.9	10.4	2.81	2.09	.201
.502	.295	116.0	105.7	100.8	134.0	00	4.9	10.3	2.78	2.12	.206
.514	.289	116.2	105.6	100.8	133.8	0	4.8	10.6	2.86	1.94	.183
-- average						.175	--				
<u>Boiling - stirred</u>											
.526	.317	117.0	106.3	100.85	134.2	282	5.45	10.7	2.89	2.56	.239
.503	.313	116.5	106.3	100.95	133.9	303	5.35	10.2	2.75	2.60	.255
.497	.298	115.8	105.7	100.75	133.8	296	4.95	10.1	2.72	2.13	.211
.492	.303	116.0	105.9	100.8	134.0	315	5.1	10.1	2.72	2.38	.236
.471	.302	115.6	105.9	100.8	133.4	291	5.1	9.7	2.61	2.49	.257
-- average						.239	--				
<u>85° - stirred</u>											
.814	.352	109.4	91.3	84.75	133.8	296	6.55	18.1	4.89	1.55	.092
.807	.344	109.5	91.5	85.0	133.4	286	6.5	18.0	4.85	1.65	.092
.814	.342	109.55	91.5	85.05	134.0	288	6.45	18.05	4.86	1.59	.088
.823	.335	109.5	91.35	85.2	133.8	290	6.15	18.15	4.90	1.25	.069
.816	.325	108.7	90.8	84.8	133.6	286	6.0	17.9	4.83	1.17	.066
.810	.328	109.1	91.2	85.1	132.2	300	6.1	17.9	4.83	1.27	.071
-- average						.079	--				



RUN 3. TABLE III.

concluded.

1	2	3	4	5	6	7	8	9	10	11	12
Milivolts			Temperature			RPM of Sol	t <sub>2</sub>	Temperature differences			
E <sub>1</sub>	E <sub>2</sub>	B	A or D	C & Sol	Oil			t <sub>1</sub>	t	x	$\frac{x}{t}$
av.									t x.27 2	t-t <sub>1</sub>	1

70° stirred

.447	1.095	104.1	79.7	69.5	134.5	312	10.2	14.4	3.89	6.31	.438
.454	1.091	104.05	79.6	69.7	136.0	325	9.9	14.45	3.90	6.0	.414
.441	1.030	102.6	74.6	69.8	134.0	300	9.8	13.0	3.51	6.29	.484
.428	1.015	101.75	79.1	69.75	133.0	303	9.35	12.65	3.41	5.94	.470
.423	1.001	101.7	79.3	70.00	132.8	306	9.3	12.4	3.35	5.95	.460
.427	1.030	102.2	79.25	69.8	133.0	309	9.35	12.05	3.25	6.10	.505
-- average						.466	--				



RUN 5. Table V.

Sodium Hydrate 40 grams per liter.

Oil R.P.M. 150.

1	2	3	4	5	6	7	8	9	10	11	12
Millivolts			Temperatures			RPM Temp. Difference					
E <sub>1</sub>	E <sub>2</sub>	B	A or D	C or I	Oil	Sol.	t <sub>s</sub>	t <sub>1</sub>	t	x	$\frac{x}{t_1}$
av									t <sub>1</sub> x.27	t <sub>2</sub> t	$\frac{x}{t_1}$

Boiling - stirred

.569	.226	115.2	103.2	99.75	134.2	287	3.45	12.00	3.24	0.21	.0175
.554	.219	114.55	103.0	99.75	134.0	300	3.25	11.55	3.12	0.13	.0113
.559	.219	114.75	103.0	99.75	133.7	297	3.25	11.55	3.12	0.13	.0113
.553	.223	114.75	103.15	99.75	133.7	290	3.40	11.60	3.13	0.27	.0141
-- average						.0153 --					

Boiling -- direction of stirring reversed

.618	.220	115.9	103.0	99.75	133.6	309	3.25	12.90	3.48	-.13	--
.627	.230	116.4	103.25	99.75	134.2	314	3.50	13.15	3.55	-.05	--
.620	.221	115.8	103.0	99.75	134.0	290	3.25	12.80	3.40	-.02	--
.614	.225	115.8	103.2	99.75	134.0	312	3.45	12.60	3.40	0.05	.0039
.595	.242	116.0	103.6	99.75	133.9	300	3.65	12.40	3.35	0.50	.0403

Boiling - unstirred

.639	.219	116.4	102.45	99.7	134.2	0	3.25	13.45	3.63	-.38	---
.637	.216	116.2	102.8	99.7	134.0	0	3.10	13.40	3.62	-.52	---
.626	.215	115.95	102.8	99.7	133.9	0	3.10	13.05	3.52	-.42	---
.579	.227	115.3	103.2	99.7	134.3	0	3.50	12.10	3.27	0.23	.190
.559	.220	114.55	103.0	99.7	133.7	0	3.30	11.55	3.12	0.18	.155
.553	.214	114.4	102.8	99.7	133.7	0	3.10	11.60	3.13	-.03	

85° - stirred

.958	.320	112.2	91.1	85.2	134.0	300	5.90	21.10	5.70	0.20	.0095
.967	.330	112.5	91.25	84.95	133.8	306	6.30	21.25	5.80	0.50	.0235
.968	.327	112.0	90.8	84.9	133.7	300	5.90	21.20	5.77	0.43	.0061
.958	.334	112.5	91.3	85.1	134.0	309	6.20	21.20	5.77	0.43	.0203
.937	.333	111.8	91.2	85.0	134.0	320	6.20	20.60	5.56	0.64	.0310
.938	.327	111.9	91.25	85.2	133.0	312	5.95	20.65	5.57	0.38	.0184
-- average						.0181 --					



RUN 6. TABLE VI.

Sodium Hydrate 40 grams per liter.

Oil R.P.M. 150.

Note:-- This run and the following were made with the heat insulating jacket on the apparatus.

1	2	3	4	5	6	7	8	9	10	11
Milivolts		Temperatures				RPM of Sol	Temperature differences.			
$E_1$ av.	$E_2$	B	A or D	C & Sol	Oil		$t_2$	$t_1$	$t$	$\frac{x}{t} \times .27, t_2 - t$

Boiling - unstirred

.964	.218	123.25	103.0	99.75	133.75	0	3.25	20.25	5.46	-2.21
.957	.213	123.0	102.6	99.75	133.8	0	2.85	20.4	5.51	-2.66
.963	.215	123.25	102.65	99.75	133.7	0	2.80	20.6	5.56	-2.76
.979	.219	123.5	103.0	99.75	133.8	0	3.25	20.5	5.54	-2.29
.954	.220	122.9	103.1	99.8	134.1	0	3.3	19.8	5.35	-2.05
.965	.214	122.8	102.7	99.8	134.0	0	2.9	20.1	5.42	-2.52

Boiling - stirred

.955	.232	123.7	103.2	99.8	134.0	270	3.3	20.5	5.54	-2.14
.954	.220	123.7	103.25	99.95	134.0	270	3.3	20.55	5.55	-2.25
.956	.218	123.75	103.20	99.95	134.1	280	3.25	20.75	5.60	-2.35
.931	.220	122.7	103.3	100.0	134.1	270	3.3	19.4	5.34	-2.04
.957	.219	123.75	103.25	100.0	134.1	270	3.25	20.50	5.54	-2.29
.967	.232	123.75	103.3	99.8	134.2	290	3.5	20.45	5.53	-2.03

85° - stirred

1.431	.341	122.6	91.5	85.2	133.0	290	6.3	31.1	8.4	-2.1
1.458	.340	122.4	91.35	84.95	132.5	306	6.4	31.05	8.35	-1.95
1.476	.357	123.8	91.75	84.95	133.9	296	6.8	32.05	8.65	-1.75
1.476	.352	123.85	91.8	85.2	134.0	306	6.6	32.05	8.65	-2.05
1.478	.354	123.9	91.85	85.2	134.2	309	6.65	32.05	8.65	-2.0
1.456	.348	123.4	91.25	84.95	134.0	309	6.3	32.15	8.67	-2.37





RUN 7. TABLE VII.

Sugar 343 grams per liter.

Oil R.P.M. 150.

1	2	3	4	5	6	7	8	9	10	11
Millivolts		B	Temperatures			RPM of Sol.	Temperature differences			
$E_1$	$E_2$		A or D	C & Sol	Oil		$t_s$	$t_1$	$t_{1 \times .27}$	$t_2 - t_x$
av.										

Boiling - unstirred.

.888	.245	121.75	103.2	99.35	133.8	0	3.85	18.55	5.01	-1.16
.894	.247	122.2	103.25	99.35	133.9	0	3.90	18.95	5.12	-1.22
.900	.241	122.05	103.15	99.35	133.7	0	3.80	18.90	5.10	-1.30
.898	.243	122.1	103.2	99.35	134.0	0	3.90	18.9	5.10	-1.20
.906	.241	122.05	103.15	99.35	134.0	0	3.80	18.90	5.10	-1.30

Boiling - stirred

.888	.245	121.75	103.25	99.45	133.8	280	3.80	18.50	5.00	-1.20
.896	.233	121.90	103.05	99.45	134.0	402	3.50	18.85	5.09	-1.59
.976	.220	123.4	102.75	99.45	133.8	383	3.30	20.85	5.60	-2.50
.968	.233	123.3	103.05	99.45	133.8	310	3.50	20.25	5.47	-1.97
.976	.234	123.6	103.05	99.45	133.8	310	3.50	20.55	5.55	-2.05
.998	.237	124.25	103.1	99.45	133.8	310	3.65	21.15	5.72	-2.07

85° stirred

1.431	.309	121.75	90.5	84.95	133.5	320	5.65	31.25	8.45	-2.80
1.492	.313	123.10	90.6	85.0	134.2	300	5.60	32.4	8.75	-3.15
1.466	.323	122.6	91.0	85.1	134.9	300	5.90	31.6	8.54	-2.64
1.430	.327	121.8	90.75	84.9	134.0	296	5.85	30.05	8.12	-2.27
1.412	.319	121.4	90.7	84.95	133.9	290	5.75	30.7	8.30	-2.55
1.412	.311	121.2	90.5	84.95	133.9	286	5.55	30.7	8.30	-2.75
1.426	.311	121.5	90.5	84.9	134.0	290	5.6	31.0	8.37	-2.77



RUN 8. TABLE VIII.

Sodium Sulfate 142.2 grams per liter

Oil R.P.M. 150.

1	2	3	4	5	6	7	8	9	10	11
Milivolts		Temperature				RPM	Temperature dif-			
E <sub>1</sub>	E <sub>2</sub>	B	A or D	C	Oil & Sol	Sol. t <sub>s</sub>	t <sub>1</sub>	t	ferences.	
av.										

Boiling - unstirred.

1.050	.237	125.4	103.4	99.6	134.0	0	3.8	22.0	5.94	-2.14
1.012	.228	124.5	103.2	99.65	133.7	0	3.55	21.3	5.75	-2.25
1.050	.235	125.25	103.4	99.7	134.0	0	3.7	21.85	5.90	-2.2
1.030	.232	125.0	103.3	99.7	133.8	0	3.6	21.7	5.86	-2.26
1.059	.230	125.45	103.25	99.7	134.3	0	3.45	22.2	6.00	-2.55
1.063	.236	125.65	103.4	99.7	134.2	0	3.7	22.45	6.27	-2.47

This run could not be carried farther as the storage cell supplying current to the potentiometer gave out.



# TABLE IX.

Summary of  $\frac{x}{t_1}$  for various solutions., stirred  
at about 300 R. P. M.

Run	Solution	70°	85°	Stirred	Boiling Unstirred
2	Water	.610	.113	.151	.091
3	Sodium Chlor- ide 58.5 gr per liter	.466	.209	.238	.178
4	do. 117. gr per liter	N. M.*	.079	.239	.175
5	Sodium Hy- drate 40 gr. per lit- er.	N. M.	.0181	.0153	N. R.
6	Same.	N. M.	N. R.**	N. R.	N. R. )
7	Sugar	N. M.	N. R.	N. R.	N. R. )
8	Sodium Sulfate 142 g. per liter	N. M.	N. M.	N. M.	N. R. )

\* N. M. Observations not made.

\*\* N. R. (X) Takes negative value so  $\frac{x}{t_1}$  cannot  
be computed.

\*\*\* Apparatus lagged with fossil flour.

$\frac{x}{t_1}$  is the ratio of the temperature drops between  
the plate and solution and in 18.5 cm. in the plate.



Recommendations.

With slight changes the apparatus as used in this investigation ought to give very satisfactory results. The hole (3) Plate II is not deep enough, and makes the couple placed here somewhat sensitive to changes in the temperature of the oil. This hole could be made  $1/2$  to 1 cm. deeper. Better thermocouples ought to be used. The wires can be tested for homogeneity<sup>(1)</sup> so that the calibration curve of each couple is the same and the troublesome effects of potentials in the wires be guarded against. It would also be well to calibrate the couples by the method of fixed points and it is not necessary to go over  $150^{\circ}\text{C}$ . If the calibration is accurate, the temperature of couple (2) is best measured by reading its potential directly.

Some crude experiments were made measuring the elongation of a wire carrying current in various solutions. It was found that the linear expansion of a copper wire 6 inches long immersed in a solution was considerable and

(1) For testing and calibrating of copper-constantan thermocouples, see articles by W. P. White in

Physical Review, 31 Aug. 1910, pp. 135, & 159.





that with a crude deflectometer differences of two or three degrees were easily measured. With a cathetometer the elongation can be measured much closer. Rogovsky experimented with a silver wire in water but did not carry the work farther. (See bibliography "Films and the Transfer from A Partition to a Medium", page 49.)

An apparatus in which the temperature of a metal wire is measured in the manner suggested above ought to be accurate enough for practical purposes for additional experiments in which the temperature difference between a metal and a liquid is desired.



A p p e n d i x .

Thermocouples and their Calibration.

The couples were made of copper and constantan wires fused in an arc, making a bead slightly less than 1 m.m. in diameter. The copper was No. 22 B. & S. and cotton covered, the constantan was No. 24 and bare. After fusing the junction the cotton insulation of the copper wire was twisted down toward the bead and then tightly wound with a single winding of buttonhole silk to make sure that there was no possibility of contact between the two wires. The two wires were then bound together except at the bead with the silk thread for a distance of about four inches and then given several coats of shellac.

The couples were calibrated against standard thermometers in a cylinder oil bath. The silk insulation of the couples was protected by a glass tube but the bead was left unprotected and immersed directly into the oil. The oil was heated in a glass jar placed in a vertical electric furnace and stirred continuously while the readings were being made. Two couples were calibrated at the same time and they were placed so that the beads were the same depth as the middle of the thermometer bulb and about half an inch from it near the center of the bath.



Couple (C) was placed in a small glass tube the end of which was sealed. At first the calibration of this couple was not satisfactory as the points taken while the bath was being heated were not the same as those taken when the bath was cooling. About an inch was amputated from the couple and the ends re-fused and the sealed end of the tube was blown out to give a thinner wall. The calibration was then found satisfactory and the couple was used in this condition in the experimental work.

The ice bath for the cold junctions was a double walled can the space between the walls being filled with fossil flour. A drain pipe allowed the water to flow out of the ice chamber. The cold junctions were soldered to copper leads and placed in glass tubes which were kept in the cracked ice. A double throw, double pole mercury contact switch was connected between the potentiometer and the couples so that either one could be connected to the potentiometer. The potentiometer was a Leeds & Northrup Type K instrument No. 8728, on which the E.M.F. could be read directly when the current flowing through it was properly adjusted by standardizing against the standard cell. The slide wire of the potentiometer was calibrated before use and it was found correct to 0.002 of a turn, or **error** 0.002 millivolts. This is within the experimental, so the



correction to observed values was not applied. The same standard cell was used throughout all the experiments and its value as calibrated by the Physics Department is given as 1.0182 volt. A wall D'Arsonval galvanometer, Type H, made by Leeds & Northrup especially for potentiometer work was used. A 4-volt portable storage cell was used as a source of E. M. F. to supply the current through the instrument. It had to be recharged frequently.

A set of three Siebert and Kühn certified thermometers were used. Their temperature ranges were 0-100°, 100° - 200° and 200° - 300° approximately. In finding the fixed points on the calibration curves care was taken to have the rate of change of temperature of the bath very low in order to reduce the lag between the thermometer and couples. It was customary to note the potential of the couples while the bath was increasing and decreasing in temperature near the desired temperature, the thermometers being read to .05° by the aid of a microscope.

The following table gives the calibration data for each couple.

Note:--

Copper was chosen as one element instead of iron as it was thought that the copper wire would show greater homogeneity than iron. The





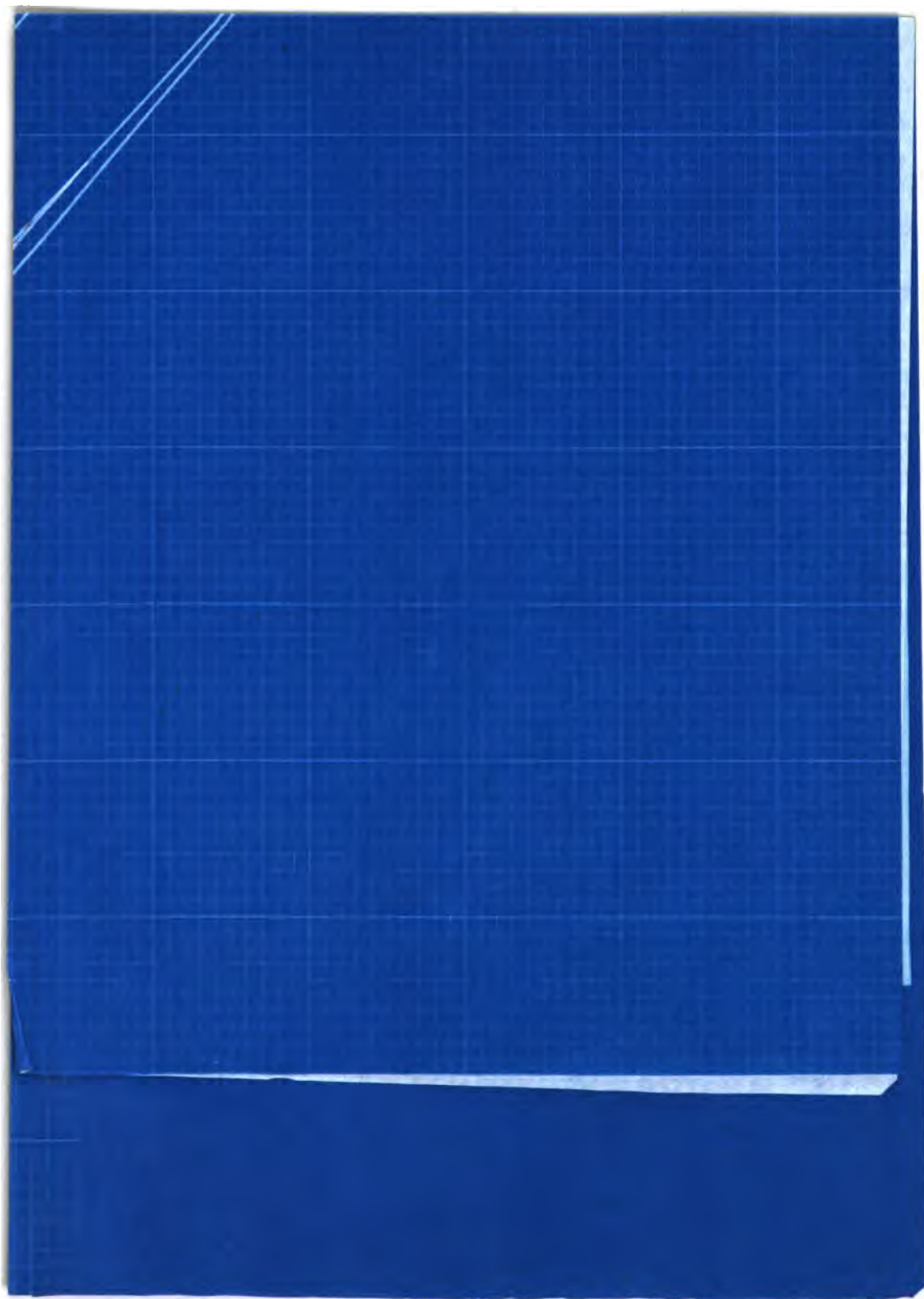
The wire was not tested for this quality which is a factor to be considered in the making of sensitive thermocouples. For a duscussion of this see "The Thermo Couple as a Precision Instrument", W. P. White, Physical Review, 1910. 31 p. 135.



# CALIBRATION CURVE DATA FOR THERMOCOUPLES

Temp.	Millivolts.			
<u>C°</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>
10	0.350	0.365	0.350	0.360
20	0.720	0.730	0.715	0.735
30	1.110	1.120	1.075	1.120
40	1.500	1.500	1.450	1.495
50	1.915	1.905	1.845	1.875
60	2.330	2.325	2.240	2.280
70	2.745	2.745	2.645	2.690
80	3.185	3.185	3.055	3.120
90	3.635	3.640	3.445	3.550
100	4.070	4.080	3.860	3.96
110	4.501	4.505	4.360	4.425
120	4.970	5.017	4.810	4.880
130	5.440	5.490	5.225	5.405
140	5.925	5.940	5.730	5.840
150	6.435	6.430	6.205	6.320
160	6.940	6.920	6.695	6.820
170	7.445	7.420	7.180	7.330
180	7.960	7.930		7.850
190	8.470	8.430		8.350
200		8.945		







Approved:--

O. L. Kewalk

June 15 1911.









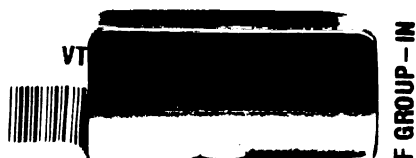


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**NON-CIRCULATING**



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